



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

**MC4 101057394**

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

**Deliverable D6.6: Assessment of parts made from recycled material**

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

Start date of project: 1st April 2022

Duration: 36 months

Coordinator:  
Christian Eitzinger  
Profactor

Revision 1

Lead Beneficiary: MANAGING COMPOSITES  
Contributions by: AMURA, FIDAMC, GAIKER, LAB23, NOMA, VDL

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

## Contents

1.	INTRODUCTION AND OBJECTIVES .....	4
2.	AUTOMOTIVE COMPONENTS MADE FROM RECYCLED MATERIALS .....	5
2.1	Recycling and manufacturing process description .....	5
2.2	Technical specifications assessment .....	6
2.3	Virgin materials product comparison .....	9
2.4	Economical evaluation .....	11
2.5	Design and manufacturing lessons learnt .....	12
3.	AUTOMOTIVE COMPONENTS MADE FROM RECYCLED MATERIALS AT LAB SCALE .....	14
3.1	Recycling and manufacturing process description .....	14
3.2	Technical specifications assessment .....	15
3.3	Virgin materials product comparison .....	17
3.4	Economical evaluation .....	18
3.5	Design and manufacturing lessons learnt .....	18
4.	BOAT COMPONENTS MADE FROM RECYCLED MATERIALS .....	19
4.1	Recycling and manufacturing process description .....	19
4.1.1	Recycling Process .....	19
4.1.2	Manufacturing Process .....	19
4.2	Technical specifications assessment .....	20
4.2.1	Materials and Laminate Configuration .....	20
4.2.2	Inspection and Final Product Evaluation .....	21
4.3	Virgin materials product comparison .....	22
4.3.1	Availability and Development of Recycled Material .....	23
4.3.2	Key Differences Between Recycled and Virgin Materials .....	23
4.4	Economical evaluation .....	25
4.4.1	Comparison of Material and Process Costs .....	25
4.4.2	Impact on Operational Costs and Process Efficiency – Conclusions .....	26
4.5	Design and manufacturing lessons learnt .....	27
4.5.1	Potential Applications in the Nautical Industry .....	27
5.	BOAT COMPONENTS MADE FROM RECYCLED MATERIALS AT LAB SCALE .....	29
5.1	Recycling and manufacturing process description .....	29
5.2	Technical specifications assessment .....	29
5.3	Virgin materials product comparison .....	30
5.4	Design and manufacturing lessons learnt .....	30
6.	AEROSPACE COMPONENTS MADE FROM RECYCLED MATERIALS .....	31
6.1	Recycling and manufacturing process description .....	31
6.1.1	Aerospace use-case .....	31
6.1.2	Scrap transformation process .....	31
6.1.3	Use-case manufacturing description .....	33
6.1.4	Full circular process chain .....	33
6.2	Technical specifications assessment .....	34
6.2.1	Demonstrator 0: Leading-edge rib use-case developed by RTM technology (baseline) .....	34
6.2.2	Demonstrator 1: Leading-edge rib use-case developed by hand lay-up & vacuum bag .....	35
6.2.3	Demonstrator 2: Leading-edge rib use-case developed by hot-press process and 3 plies ....	35
6.2.4	Demonstrator 3: Leading-edge rib use-case developed by hot-press process and 2 plies ....	36
6.2.5	Characterization Results: Fibre Volume Fraction (FVF) & Void Content .....	37
6.3	Virgin materials product comparison .....	39
6.3.1	Elastic Modulus Analysis .....	40
6.3.2	Mechanical Strength Analysis .....	40
6.4	Economical evaluation .....	41
6.5	Design and manufacturing lessons learnt .....	43
7.	SPORT EQUIPMENT MADE FROM RECYCLED MATERIALS .....	45

7.1	Recycling and manufacturing process description.....	45
7.2	Technical specifications assessment .....	46
7.2.1	Kayak.....	46
7.2.2	Paddle.....	49
7.3	Virgin materials product comparison.....	54
7.3.1	Kayak.....	54
7.3.2	Paddle.....	57
7.4	Economical evaluation .....	58
7.5	Design and manufacturing lessons learnt .....	59
8.	URBAN FURNITURE MADE FROM RECYCLED MATERIALS.....	61
8.1	Recycling and manufacturing process description.....	61
8.2	Technical specifications assessment .....	62
8.3	Virgin materials product comparison.....	62
8.4	Economical evaluation .....	64
8.4.1	Material Costs.....	64
8.4.2	Process Costs .....	65
8.4.3	Comparison: Recycled GFRC vs. Virgin Materials (e.g., Construction Stone Grit) .....	65
8.4.4	Other Economic Considerations: .....	65
8.4.5	Conclusion .....	66
8.5	Design and manufacturing lessons learnt .....	66
9.	CIVIL ENGINEERING COMPONENTS MADE FROM RECYCLED MATERIAL.....	68
9.1	Recycling and manufacturing process description.....	68
9.2	Technical specifications assessment .....	69
9.3	Virgin materials product comparison.....	72
9.4	Economical evaluation .....	73
9.5	Design and manufacturing lessons learnt .....	74
10.	CONCLUSIONS .....	76

# 1. INTRODUCTION AND OBJECTIVES

The early 2000s marked the emergence of the widespread use of composite materials in industry. The volume of parts made from composite materials has been steadily increasing year after year. It is, of course, the excellent mechanical performance, relatively easy manufacturing solutions, and production costs that compete with those of metal materials that have driven the rise of composite materials.

However, the upcoming arrival of Industry 5.0, which encourages, among other values, eco-friendly and sustainable manufacturing practices such as the use of renewable energy sources, material recycling, and waste reduction, could slow the widespread use of composite materials, which are considered to be poorly recyclable. While composite materials have proven their technical performance up to now, they must now demonstrate their recyclability in order to integrate into a greener industry of tomorrow. In this context, the MC4 project aims at developing and validating new recycling techniques for composite materials.

This deliverable concerns the evaluation of parts made from recycled materials developed during the project. To prove the validity of each recycling method addressed in the project, demonstrators are designed and manufactured. A prototype of a real part is an important phase to validate the viability of a project at a pre-industrial scale. It also helps to resolve doubts on many issues, not only from a theoretical perspective regarding profitability or environmental impact, but also, and most importantly, from a practical aspect. The feasibility of the design, mechanical performance, and manufacturability are essential points that are evaluated during the prototype development phase. In this perspective, demonstrators are created to validate the short- and long-term recycling technologies of composite materials made with glass fibre and carbon fibre.

This deliverable outlines the key steps in the use of recycled materials in the development of the various demonstrators. It also provides a review of the use of these materials compared to virgin materials from a technical and economic standpoint, along with conclusions and feedback on the use of these recycled materials.

## 2. AUTOMOTIVE COMPONENTS MADE FROM RECYCLED MATERIALS

### 2.1 Recycling and manufacturing process description

The End of life (EoL) material from the bus side wall will be shredded into “fibres” of 1 to 10 cm. This was achieved by transporting the side walls to the external company CRC for mechanical shredding, and then delivering them back to VDL Fibertech as glass fibres of 1 to 10 cm. These fibres still contain the foam and resin, from the original part. They are used as a filler and to provide extra strength in the new side skirt of a bus.

The RTM mould is first layered with virgin unidirectional glass fibres, on which the shredded fibres are placed, in the mould. The foaming resin is then applied, followed by a final layer of virgin glass fibres. After this the mould is closed for 4 hours for curing. The final product that comes out from the RTM mould is a side skirt ready for post processing. At that stage, the excess material is removed and the side skirt is machined to the right dimensions. The hook piece is glued to the side skirt. Because this piece has a specific angle, it is impossible to place it in the mould initially. After these steps, the part is ready to be attached to the bus. Below the chart flow of the process is depicted.



Figure 1. RTM mould of the bus skirt

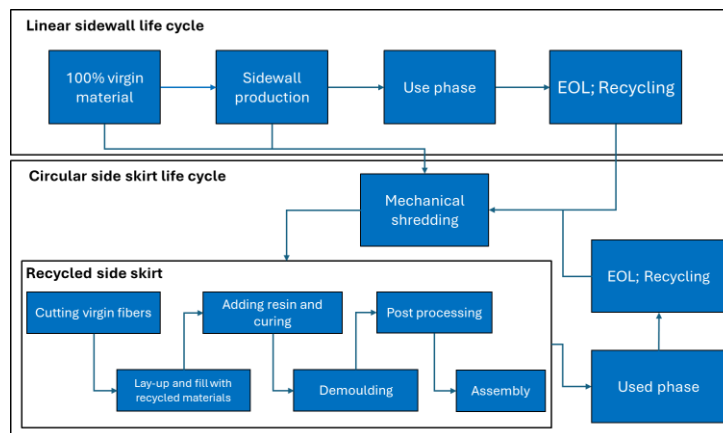


Figure 2: Process chart flow.

## 2.2 *Technical specifications assessment*

---

The side skirt must meet several technical specifications, as it serves as a bumper for the bus. It needs to withstand impacts, as well as various weather conditions, since the bus will be driven through different terrains and exposed to all kinds of weather.

### Material Used

- Foam Epoxy Resin: Cellular Epoxy Foam (1000g).
- Hardener: DM 03 (310g)
- Recycled fibres: Recycled glass fibres 1-10 cm from CRC (1000g)
- Virgin fibres: 2 layers of Unifilo 640UD gsm (300g)
- Gel coat: Bufa getcoat (300 g)

The requirements are split into qualitative and quantitative requirements.

### Quantitative requirements

- Young modulus > 2 GPa
- Bending strength > 170 MPa
- Tensile strength > 170 MPa.
- Density < 1800 kg/m<sup>3</sup>
- Thermal conductivity < 0,21 W/mK
- Operating temperature within -40 and 90 degrees Celsius
- Water absorption < 2 %

### Qualitative requirements

- Excellent surface quality and should be paintable.
- Edged from drilling and cutting of the product must be smooth.
  - Chemical resistance against several chemicals: ethanol, IPA, brake fluid, hydrochloric acid, sodium hydroxide, glycol, diesel and AdBlue (32.5% solution of urea in demineralized water)
- Compatible with current mounting fixtures

For clarity, the requirements are shown in the table below. Here it is also visible, how these requirements will be tested. If the side skirt meets the requirements, it will be tested on a bus.

The shredded materials were used for low complexity products, such as a rain barrel but these fibres will be also used for automotive products, such as a side skirt for a bus. For this reason, the mechanical properties were investigated and presented in Table 1.

*Table 1 Mechanical properties of original side skirt.*

Properties	Value
Youngs modulus	20 N/mm <sup>2</sup>
Tensile strength	170 N/mm <sup>2</sup>
Bending strength	170 N/mm <sup>2</sup>
Density	1800 kg/m <sup>3</sup>
Thermal conductivity	0,21 W/mk
Operating temperature	-40 to 90 C
Water absorption	2%

From the testing, with the Distitron resin, it was clear that if the bending strength was not reached then the tensile test was not reached. For this reason, only the bending strength and Youngs modulus were tested first. If the results were promising, the tensile tests and water absorption tests were then completed.

The plates made from different resins, described in chapter 2.2, were tested through a three point-bending test. For this test, the plate was cut into samples from 100 mm X 25mm and the thickness of the samples was 5 mm. From each sample five were tested. Figure 3 shows the samples while Figure 4 presents the set up for bending tests.



Figure 3. Samples of the different resin test



Figure 4. Set up for the three-point bending test

Out of all the plates, enough samples could be cut for the bending and the tensile testing, as it is apparent from Figure 3. To be time efficient, first the bending test was conducted. Here it is visible that the Youngs modulus is very low and for this reason, only the bending test was conducted. In the earlier testing it was clear that if the bending strength and Youngs modulus were low, the Tensile test would also be too low.

Table 2 Results of three-point bending test.

Samples	Bending strength N/mm <sup>2</sup>	Youngs Modulus N/mm <sup>2</sup>	Maximum load N
1. Epoxy foam resin	12,3 +/- 1,9	957 +/- 114	53 +/- 7
1. Epoxy foam resin. with CFM	61,9 +/- 6,9	3312 +/- 422	259 +/- 21
2. PUR resin	46,6 +/- 8,4	1412 +/- 444	219,8 +/- 29,5
3. PUR resin. with CFM	138,7 +/- 7,8	3938 +/- 115	637,9 +/- 35
4. PET resin	57,3 +/- 17,5	3508 +/- 499	230,7 +/- 73
5. PET resin with CFM	109,9 +/- 21,9	4961 +/- 749	501,6 +/- 93
6. Distitron VE370SC	65,5 +/- 9,5	3956 +/- 442	282,8 +/- 49
7. Distitron VE370SC with CFM	140,9 +/- 2,8	6019 +/- 511	555,3 +/- 35

As visible in Table 2, none of the tested resin reaches the required mechanical properties. For the automotive use the product needs to be lightweight and have a good surface quality. Even though the epoxy foam resin had the lowest mechanical properties, it had the best surface quality, lowest density and less resin is required for the full fibres covering. For these reasons, the epoxy foam resin was chosen for further research on reaching the necessary mechanical requirements.

Table 3 Results bending test different virgin glass fibres.

Samples		Bending strength N/mm <sup>2</sup>	Youngs modulus N/mm <sup>2</sup>	Maximum load N
1. Plate with unidirectional 1200g/mm <sup>2</sup>		219,0 +/- 31,4	18053 +/- 1282	914,6 +/- 119,9
2. Plate with unifilo. 640g/mm <sup>2</sup>		132,5 +/- 25,0	6077 +/- 1489	554,4 +/- 110,3
3. Plate with quadrax. 1200g/mm <sup>2</sup>		116,9 +/- 10,3	6114 +/- 287,9	478,5 +/- 50,1

After the tests, it was determined to use the unidirectional 1200g/mm<sup>2</sup> fibre mat for the automotive part from the table above, but for the sample for the water absorption, the test 640 g/mm<sup>2</sup> mat was used. The reason is that the virgin fibre mat does not have an impact on the water absorption.



Figure 5 Test set up and sample for water absorption testing.

Samples of epoxy foam resin plates with gelcoat and sealed edges and samples of epoxy foam resin without gelcoat and sealing were sent to Windesheim, a university that also specializes in recycling of composites in Zwolle. The plates were tested on water absorption by submersing the sample in a water bath at 23 °C and at 38 °C for 51 days. In Figure 5, the notation SE stands for the samples with only epoxy resin and recycled fibres without a seal. The notation C is for the samples with a gelcoat and sealed edges.

Table 4 Results water absorption testing

Sample	Time (h)	0	5	10	13	16	19	26
SE 23 C	% of moisture	0	0,8	2,4	3,1	5,7	6,1	11,4
SE 38 C		0	1,7	5,0	6,7	9,8	11,4	16,8
C 23 C		0	0,6	1,0	1,5	1,9	2,7	3,1
C 38 C		0	1,2	2,1	2,7	3,4	4,6	5,4

From the table above, the water uptake is quicker and goes to a higher lever at 38 °C than at 23 °C. The results at 23 °C are more representative for the application in a side skirt of a bus.

Furthermore, the large effect of sealing is clear: 3,1 % uptake when sealed but 16,8 % (and not at the saturation) when not sealed. Although a permanent immersion in water is not representative for the application in automotive products, it is clear that the sealing is important for protecting the composite against water ingress.

### **Quality inspection**

Visual inspections were conducted at various stages of the manufacturing process to identify potential defects and assess the quality of the laminate. Special focus was placed on the following aspects:

- Laminate: Ensuring uniform distribution of recycled material.
- Dry spots: resulting from uneven reinforcement distribution.
- Surface defects: Identifying porosity, roughness, waviness and discolouration
- Presence of pinholes in the surface of laminate, caused by the composition of foam resin and the dispersed fibres structure of recycled reinforcements.

### **Results**

- Laminate: non uniform distribution of the recycled material, is attributed to manual dispersion of the material in the mould.
- Dry spots and pinholes: Prevent them by using a layer of gel coat.
- Surface defects: Achieved a smooth surface finish A+ with strong adhesion of the gel coat, improving weatherproofing of the part such as moisture, UV resistance and corrosion resistance.

The evaluation of the side skirt demonstrated the viability of using recycled glass fibre in automotive parts and applications. However, it presented several challenges, including the availability of the material from the recycling companies and suppliers, and reduced mechanical properties compared to traditional glass fabrics. To achieve cost efficiency for the product, an automated production line needs to be implemented. These factors required specific modifications in the manufacturing process, especially in the designing process of the mould and the laminate, in order to achieve the optimal results.

## ***2.3 Virgin materials product comparison***

---

### **Virgin material**

The virgin material product is made with aluminium and the technology is extrusion. This part is made in one piece and cut to the right size. This results, in a thin part (3mm) with the inserts on the right places. The downside of this material and process is that the part is quite flimsy and needs to be painted into the desired colour. Because this material is widely used in the industry and its production method (extrusion) has been known for many years, very good repeatability is achieved.

### **Recycled material**

The part made from recycled materials (shredded glass fibres, foaming epoxy resin and virgin internal recycled unidirectional glass fibres) is strong, stiff but lightweight. It is even lighter than the virgin material part, weighing 2.8 kg compared to 3.2 kg per meter of side skirt. The advantage of this technology is that the correct colour can be added to the mould at the start of the process, ensuring that the part comes out in the desired colour. The technology used is a combination of BMC and RTM, made in a RTM Mould.



Figure 6. skirt skirts with different colours attached to the bus

Working with recycled fibres presents several challenges, particularly related to dust generation and the uniform distribution of fibres within the mould. To address these issues, a collaboration with Windesheim University was undergone to develop effective solutions. In addition, achieving a uniform distribution of fibres in the mould is essential to ensure the quality of the final product. Uneven distribution can lead to defects, dry spots and waving surface.

Furthermore, the prototype mould, with dimensions of 1000mm x 500mm, had limited capacity, restricting the ability to conduct proper testing on a bus side skirt part. Based on these difficulties Windesheim University provided a solution involving a shaker machine equipped with a belt conveyor. This system automates the process of moving the shaker up and down, ensuring the fibres are evenly dispersed within the mould. Additionally, the upside of the technology is that at the beginning of the process the right colour can be added to the mould, resulting in the part being produced in the right colour.

To mitigate dust generation, the automated line must be housed in a room with good air flow and vacuum filtration. This will help to maintain a safe and clean working environment. Another difficulty is that a hook part, is required to be attached later to the side skirt. The presence of this hook part makes impossible the side skirt to demould.

By implementing these solutions, the aim is to improve the efficiency and quality of the production process, ensuring that the recycled fibres are handled safely and distributed evenly within the moulds.

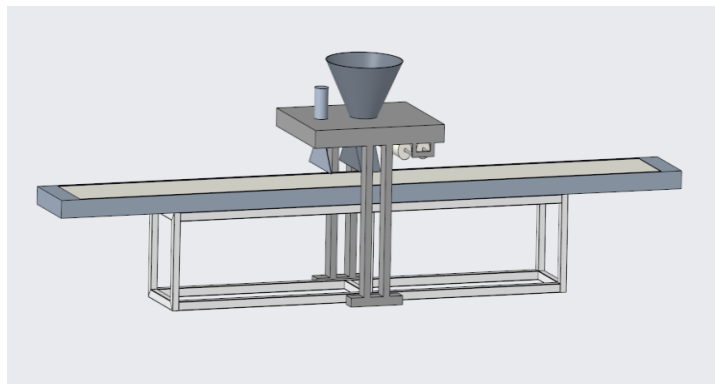


Figure 7. Automate pilot line

## 2.4 Economical evaluation

From Table 5, the cost comparison between the recycled side skirt and the current aluminium side skirt shows a notable difference in overall expenses. The recycled side skirt costs 90.48 euros per part, whereas the current aluminium side skirt costs 110 euros per part. This represents a cost saving of 19.52 euros per side skirt when choosing the recycled version.

The lower cost of the recycled side skirt is primarily due to the use of inexpensive recycled materials (0.25 euros per side skirt) and leftover virgin unidirectional fibres from production, which effectively reduces material expenses. Additional materials, such as foaming epoxy resin (16 euros per kg), gel coat (10-20 euros per kg), and 3D-printed parts (1 euro per side skirt), contribute to the total cost. However, labour and processing costs amount to 50 euros per side skirt, per hour, which influences significantly the final cost of the production.

In contrast, the current aluminium side skirt relies on more expensive raw material, costing 8 euros per side skirt and 2500 euros per ton. The labour and pultrusion process costs are not explicitly detailed, however the final price of 110 euros per side skirt is known from the supplier.

Overall, the analysis suggests that the recycled side skirt is a more cost-effective and sustainable alternative.

Table 5: Economic evaluation of recycled and current side skirt.

	<b>Recycled side skirt</b>
<b>Material</b>	<b>Cost</b>
Recycled material	250 euro per ton / 0.25 euro per side skirt
Foaming epoxy resin	16 euro per kg
Virgin unidirectional	Left over from production
Gel coat	10 to 20 euro per kg
3D printed part	0.5 euro per part/ 1euro per side skirt
Labouring/ Process	50 euro per side skirt / 1h
Profit	10% per side skirt
<b>Total</b>	<b>90.48 euro per side skirt</b>

	<b>Current Side skirt</b>
<b>Material</b>	<b>Cost</b>
Aluminium	2500 euro per ton / 8euro per side skirt
Pultrusion process/ Labouring	?
<b>Total</b>	<b>110 euro per side skirt</b>

### Cost breakdown recycled side skirt

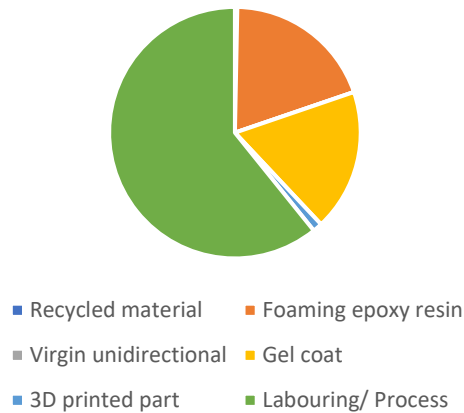


Figure 8: Cost breakdown of current side skirt.

From Figure 8 it is apparent that, labouring and processing costs have the largest portion of the total expenses. Foaming epoxy resin and gel coat also contribute notably to the cost, while recycled material, virgin unidirectional fibres, and 3D-printed parts do not play a major role at the final cost. This representation emphasizes that labour and processing are the primary cost drivers, when it comes to produce a side skirt with recycling materials. Automation of fibre distribution could help decrease the labour cost.

## ***2.5 Design and manufacturing lessons learnt***

The side skirt development within the MC4 project has facilitated the assessment of recycled glass fibre performance in the automotive industry and its incorporation into advanced manufacturing processes. Despite the complexity of producing parts with this material, the manufacturing process proved capable of producing a high-quality final product with an optimal finish, tailored to its specific characteristics.

### **Strengths of Recycled Material**

Productivity and repeatability in compression moulding processes in the RTM mould through the resin pouring, allow to reach satisfying surface quality and good compaction of different materials for automotive applications.

In applications with low structural demands or a focus on sustainability, such as non-structural parts, accessories or urban constructions, recycled materials provide an effective alternative to reduce the environmental impact of composite manufacturing.

The use of recycled glass fibre helps decrease industrial waste and reliance on virgin raw materials, supporting the sector's sustainability and emission reduction objectives. Strategies such as recycling, reusing and recovering help reduce environmental impact, conserve resources, and support sustainability goals by keeping materials in use and reducing the need for new raw materials.

### **Weakness of Recycled Material**

Because of the uncontrolled orientation and length of the fibres, the laminate has lower stiffness and strength compared to conventional fabrics, which limits its use in structural elements that require high mechanical performance. Due to the low mechanical properties additional reinforcement needs to be applied in the laminate process to meet the requirement specifications of a bus part. In the laminate

process, various types of reinforcement materials can be used to enhance the mechanical properties of the final product. These reinforcements can be selected based on the specific requirements of the part being manufactured, such as strength, stiffness, weight, and cost.

The availability of materials such as recycled glass fibre depends on the suppliers. Recycling companies face several challenges including working conditions, material quality and economic viability. These conditions require ongoing attention and innovative solutions to ensure the sustainability and efficiency of recycling operations.

### **Potential Applications in the Automotive Industry**

The MC4 project (Multi-level Circular Process Chain for Carbon and Glass Fibre Composites) has shown promising results in developing effective and economically viable recycling methods for composites made from thermoset materials, including both carbon and glass fibres. Recycled glass fibres are gaining traction in the automotive industry due to their sustainability and compliance with regulations such as the European End-of-Life Vehicles regulation.

Sectors such as public transport, including buses and trains, show great promise for incorporating recycled materials into their vehicles to reduce environmental impact. This includes interior panels and passenger equipment like tables and chairs. Additionally, building construction and urban furniture, such as joining collets, building facades, urban benches, and information poles, can also benefit from the use of recycled materials.

In conclusion, the project demonstrates that with the necessary adaptations, recycled materials can be effectively utilized to produce high-quality products. This not only enhances the efficiency of the production process but also maximizes the potential of recycled materials, contributing to a more sustainable and resource-efficient manufacturing model.

## **3. AUTOMOTIVE COMPONENTS MADE FROM RECYCLED MATERIALS AT LAB SCALE**

### ***3.1 Recycling and manufacturing process description***

---

The recycling process carried out to obtain recycled materials is the same as the one described in section 4.1.1. On the other hand, the manufacturing process used to develop the demonstrators consists of two stages:

1. Manufacturing process of the prepreg according to in-house methodology.
2. Vacuum moulding of the final part.

Manufacturing process of the prepreg with CHOMARAT textile and a vinylester-based formulation. The impregnation of the carbon fibre textile was carried out in a SCHIMIDT&HEINZMANN semi-industrial scale prepreg/SMC machine. The prepared resin formulation is deposited on two continuous films with a controlled grammage, and the fabric is placed between the two films and impregnated by compacting rollers. The impregnated textile is rolled up and, after maturation of the vinylester formulation, the material is prepared for the moulding stage.

This material was used to manufacture two demonstrators by vacuum moulding, see Figure 9:

- A simple part from the automotive sector: an insulating top cover for the back seat part of a bus
- A complex part from the nautical sector: pedestal base, described in section 5

The vacuum moulding stage consists of 6 steps:

1. Designing the layout of the prepreg in the mould to optimise structural performance.
2. Patterning and cutting of the prepreg according to the defined arrangement.
3. Placement of the prepreg. The recycled carbon fibre layers were placed according to the geometry, ensuring the correct alignment of the reinforcement.
4. Close the vacuum press and ensure a high vacuum inside the press > 950 mmHg.
5. Apply the curing cycle, 140°C for 30 min.
6. Demoulding and finishing.

The following carbon fibre reinforcements were received from Chomarat: L2, L4, C-PLY, BT 400 and BT 300, which were used to manufacture prepreg materials and moulded in a vacuum press to obtain coupons of composite material for characterization.

After studying the behaviour of these reinforcements during the different stages of manufacturing process and analysing the mechanical performance of the final composites, the BT300 nonwoven with a grammage of 300gr/m<sup>2</sup>, was selected to produce the two demonstrators.

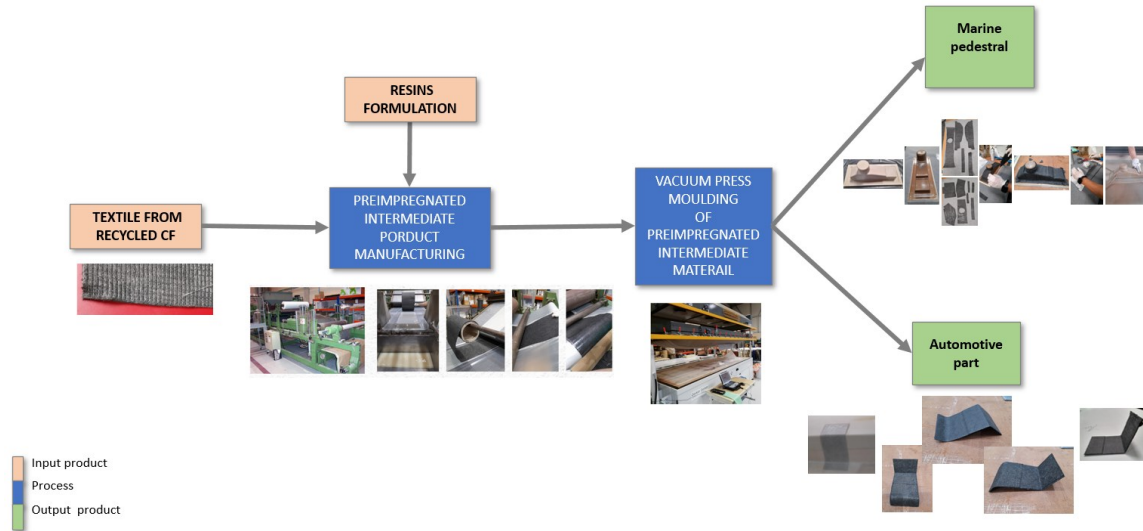


Figure 9 Flow chart of manufacturing process of preregs and final parts manufacturing

In the following images is shown the design of the simple part from the automotive sector: an insulating top cover for the back seat part of a bus. Due to limitations of textile availability the dimensions of the demonstrator were reduced from initial dimensions to width of 750mm and length of 850mm.

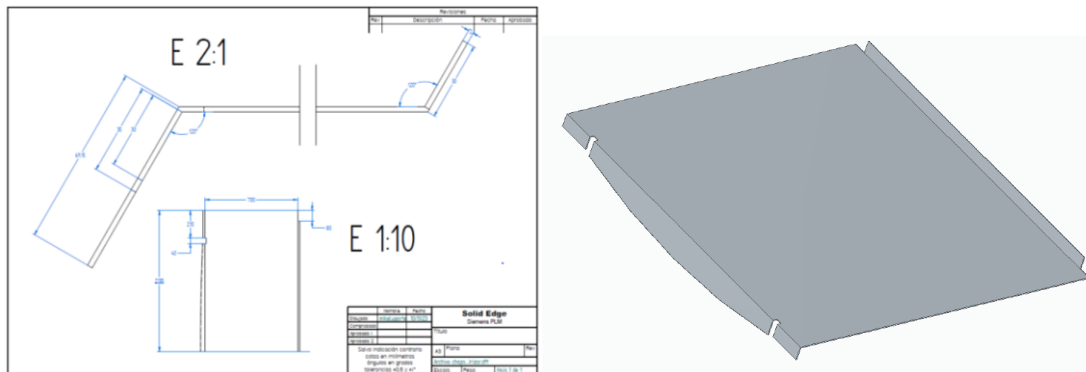


Figure 10 Cast mould plane of automotive part

### 3.2 Technical specifications assessment

Qualitative visual inspections were conducted at stages of the manufacturing process to identify potential defects and assess the quality of the prepreg and final part obtained. Specific focus was given to defects like porosity, non-impregnated areas, microbubbles and compaction.

This analysis confirmed that a high grammage vinylester formulation had to be applied to the films during prepreg manufacturing to achieve a homogeneous and adequate impregnation of the BT300 textile. It is necessary to modify the parameters of the prepreg manufacturing process in order to optimise the impregnation of the textile by minimising the formation of defects.

After improving the manufacturing process of the prepreg, its mechanical performance were studied. The following Table 6 shows the performance of the material developed for the manufacture of automotive and marine parts.

Table 6. Properties of developed CFC material with recycled textile vinylester prepreg.

	BT300	
	Average	Deviation
Tensile Strength (Mpa) UNE-EN ISO 527-4/2/2	38.7	8.35
Tensile Modulus (Mpa) UNE-EN ISO 527-4/2/2	8520	1251.37
Flexural Strength (Mpa) UNE-EN ISO 14125/AC:2002/A1	159	50.60
Flexural Modulus (Mpa) UNE-EN ISO 14125/AC:2002/A1	6530	1374.13
Interlaminar shear strength (Mpa) UNE EN ISO 14130	19	2.61
Density (gr cm <sup>-3</sup> ) UNE 53 020:1973	1.2463	0.0036

The insulating top cover for the back seat part of a bus was manufactured stacking two layers of prepreg based on BT300 according to the process described above. The visual inspection reveals proper compaction and impregnation of the material throughout the entire area of the part. Similarly, it is observed that the prepreg conforms correctly to the mould, achieving the required part geometry without the presence of defects or fibre clusters in the areas of the part with 120° angle, see Figure 11.

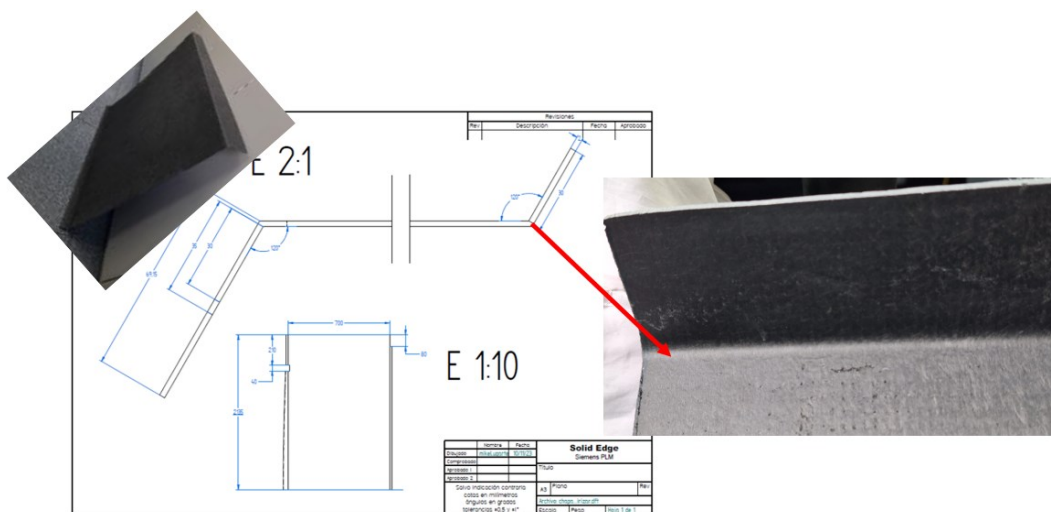


Figure 11 Detail of automotive part manufactured, 120 ° angle.

### 3.3 Virgin materials product comparison

The resin formulation based on vinylester resin was used to manufacture new prepregs with a nonwoven recycled carbon fibre (benchmark) available on the market, with chain stitching and a grammage of 317 g/m<sup>2</sup>. This prepreg was moulded to obtain coupons for mechanical characterization. The results of this characterization revealed significant differences in tensile behaviour with prepreg based on BT300, see Figure 12. However, the bending properties and interlaminar shear strength were not affected by the type of nonwoven reinforcement, see Figure 13 and Figure 14. The differences observed in the density of the cured material suggest a lower presence of porosity, likely generated by a higher compatibility of the vinylester formulation with the carbon fibre in the case of the commercial system, see Figure 14.

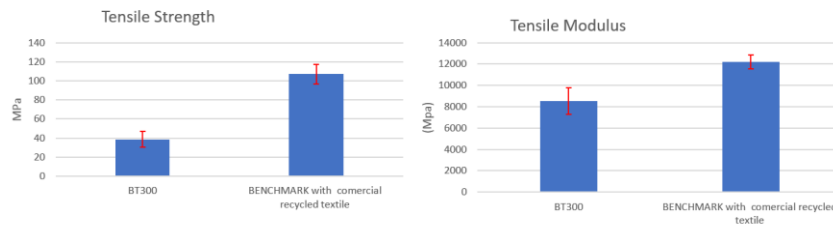


Figure 12 Comparative graph of tensile strength properties of composite materials.

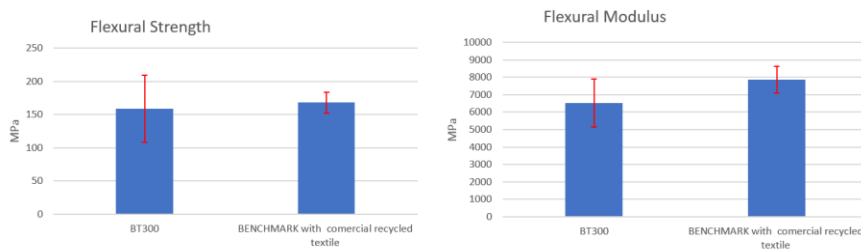


Figure 13 Comparative graph of flexural strength properties of composite materials.

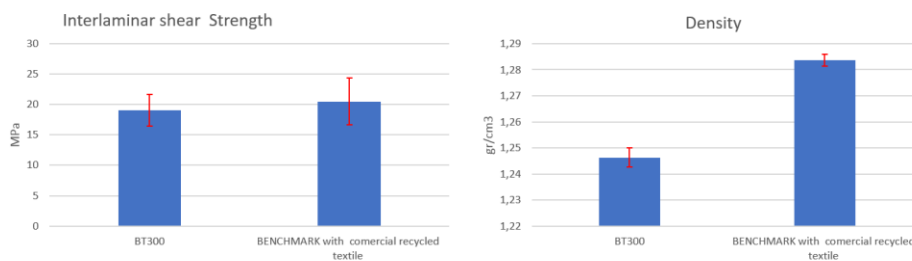


Figure 14 Comparative graph of interlaminar shear strength properties and density of composite materials.

It is important to note that the production of the prepreg material with Chomarat's nonwoven was similar to that of the benchmark nonwoven, indicating its suitability for pre-impregnate fabrication.

### 3.4 Economical evaluation

---

The total LCC for the automotive part from recycled CF is calculated at 730 €/part. The analysis is based on the inventory provided by GAIKER, while an annual production of 100 parts and 10 years of depreciation time are considered to estimate the capital expenses. For the fabrication of this part the recycled carbon fibre obtained from the production process of CHOMARAT C-PLY (OCI1505: BT300 CT3 12K-RECYCL) is used. The cost of the recycled CF is considered as zero. Table 7 below indicates the cost breakdown analysis for the automotive part.

Labour is the largest cost driver, accounting for 74% of the total manufacturing cost, followed by depreciation, which contributes 14%. However, the primary factor driving up the cost is the lab-scale nature of the process. If the limitations of the lab scale—represented by labour and depreciation costs—are excluded, the total cost is drastically reduced by 88%, bringing it down to 87 €/piece

*Table 7: Cost break-down analysis for the recycled composite automotive part (including all cost categories per FU: 1 part)*

Cost categories	€ / FU	% of total cost
Cost of Raw Materials	76,28	10,44%
Cost of Operating labor	540,00	73,87%
Cost of Utilities	10,37	1,42%
Cost of Depreciation (FCI)	104,31	14,27%
Cost of Maintenance & Repairs	0,00	0,00%
Cost of Waste Treatment	0,00	0,00%
Cost of Packaging	0,00	0,00%
Cost of Storage	0,00	0,00%
<b>Total cost</b>	<b>730,97</b>	<b>100%</b>

### 3.5 Design and manufacturing lessons learnt

---

The production of a prepreg material using mechanically recycled carbon fibre BET 300 supplied by Chomarar has been successfully achieved. However, several trials were required to control the resin formulation grammage (g/m<sup>2</sup>) and correct the impregnation of the nonwoven material, as complete impregnation was challenging to achieve. Improving the compatibility between the resin formulation and the nonwoven reinforcement could enhance the impregnation of the recycled carbon fibre reinforcement.

The prepreg developed based on recycled carbon fibre was successfully used for manufacturing a simple geometry part: back seat cover, demonstrating good compaction and stiffness.

## 4. BOAT COMPONENTS MADE FROM RECYCLED MATERIALS

### 4.1 *Recycling and manufacturing process description*

---

Amura's objective within the MC4 project is to design and manufacture a demonstrator for the nautical sector using sustainable composite materials. This demonstrator aims to assess the feasibility of integrating recycled carbon fibre into marine applications, ensuring that the material meets industry standards in terms of durability, resistance to the marine environment, and mechanical performance.

#### 4.1.1 **Recycling Process**

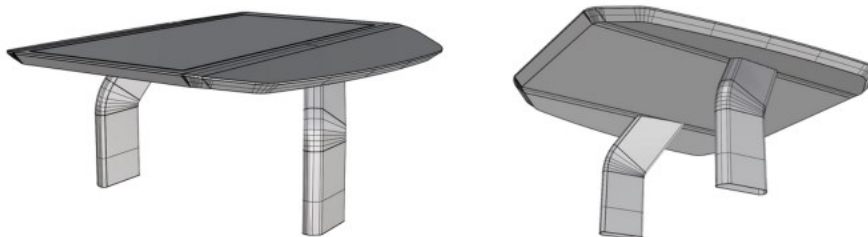
---

Although the initial plan was to use solvolysis-recycled carbon fibre from Gaiker, delays in the chemical recycling process led to the exclusive use of recycled carbon fibre sourced from Non-Crimp Fabric (NCF) production offcuts at Chomarar for the manufacturing of the T-Top demonstrator. These offcuts originate from the cutting and trimming stages of structural carbon fibre fabrics prior to resin impregnation, allowing for their reuse without significant degradation of their mechanical properties.

The recycling process involved the collection and classification of these carbon fibre residues, which were subsequently processed using mechanical stabilisation techniques. Specifically, polyester stitching consolidation methods were employed to produce non-woven reinforcements with a structure suitable for impregnation in vacuum infusion manufacturing processes. This process ensured the production of a recycled reinforcement with properties suitable for integration into composite manufacturing, guaranteeing compatibility with the production methods employed in the project.

#### 4.1.2 **Manufacturing Process**

---



*Figure 15. T- Top design*

The T-Top was manufactured using an optimised vacuum infusion process with bio-based epoxy resin. The process was carried out using a Vacmobile V2HD vacuum system, applying a pressure of 100 kPa to ensure uniform laminate impregnation. During manufacturing, environmental conditions were monitored and maintained within optimal process ranges, with atmospheric pressure values between 1023.5 and 1026.3 hPa and a controlled relative humidity between 53% and 66%, preventing adverse effects on resin impregnation. The gelation time varied between 2 and 5 hours, depending on the catalyst used, ensuring precise control of curing kinetics and dimensional stability of the laminate during infusion and polymer matrix consolidation.

- Mould preparation: Before the infusion process, the existing moulds, originally designed for manual lamination, required structural modifications to adapt to the new manufacturing strategy. The flanges were extended to improve vacuum distribution and fixation of the infusion bag, ensuring proper material impregnation and preventing resin accumulation at the edges. Subsequently, the moulds were cleaned and treated with a release agent, guaranteeing efficient part separation after curing.
- Reinforcement placement: Layers of recycled carbon fibre were arranged according to the T-Top geometry, ensuring proper reinforcement alignment to maximise structural efficiency.
- Infusion system setup: A resin distribution network and inlet and vacuum valves were positioned to control material impregnation.
- Resin infusion: Epoxy resin was introduced through a vacuum-driven pressure differential, ensuring uniform distribution without defects such as air bubbles or dry spots.
- Curing: Specific temperature and pressure parameters were maintained for the required duration to achieve complete resin polymerisation.
- Demoulding and finishing: The part was extracted from the mould, trimmed, and subjected to dimensional and structural quality control inspections.

This process enabled the manufacture of a structural component with a significant proportion of recycled material, minimising environmental impact and maximising resource reuse within the MC4 project value chain.

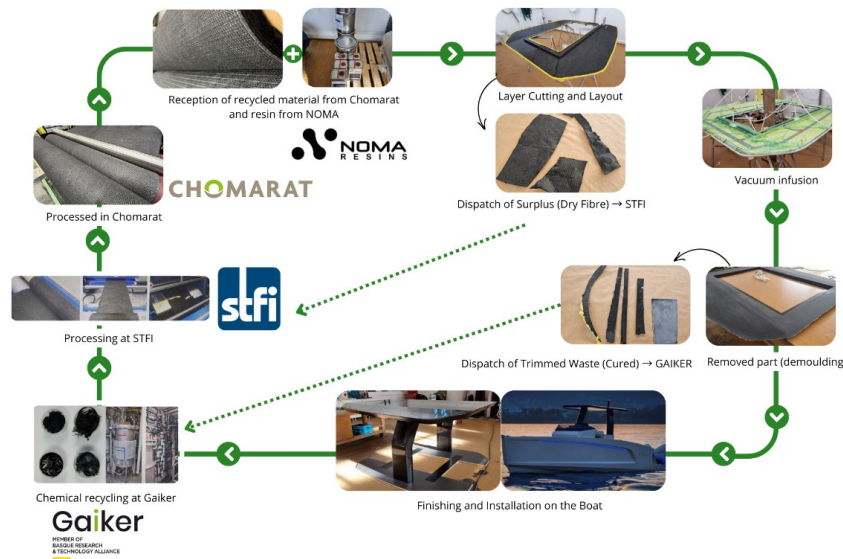


Figure 16. Flow Diagram of the Circular Process for Material in T-Top Manufacturing (Amura)

## 4.2 Technical specifications assessment

### 4.2.1 Materials and Laminate Configuration

The T-Top manufactured within the MC4 project consists of a hybrid laminate composed of approximately 82% recycled carbon fibre and 18% virgin biaxial carbon fibre, impregnated with a bio-based epoxy resin

optimised for vacuum infusion processes. The combination of these materials reduces the environmental impact of the component while ensuring the viability of the manufacturing process.

### Materials Used

- Recycled carbon fibre: OCI 1535 R BT300 CT3,4 – 24K HS (80mm), non-woven type.
- Virgin carbon fibre: 450 g/m<sup>2</sup> biaxial fabric, used in strategic areas to enhance structural strength.
- Polymeric matrix:
  - 71 kg of NOMA GREEN epoxy resin (40% bio-based).
  - 23.5 kg of NOMA LR and NOMA MR catalyst.
- Structural core: Recycled PET panels of 5 mm and 10 mm, depending on the T-Top section. Applied to increase structural rigidity and reduce overall weight.

### Laminate Configuration

The T-Top consists of three main sections, each with a specific optimised configuration to fulfil its structural function:

#### Support Pillars

- Inner layer: 1 layer of recycled carbon fibre OCI 1535 R BT300 CT3,4 – 24K HS (80mm).
- Structural core: 5 mm recycled PET panel.
- Localised biaxial reinforcement: 1 layer of 450 g/m<sup>2</sup> biaxial fabric.
- Outer layer: 1 layer of recycled carbon fibre OCI 1535 R BT300 CT3,4 – 24K HS (80mm).

#### Base of the Upper Roof Structure

- Lower layer: 1 layer of recycled carbon fibre OCI 1535 R BT300 CT3,4 – 24K HS (80mm).
- Structural core: 10 mm recycled PET panel.
- Upper layer: 1 layer of recycled carbon fibre OCI 1535 R BT300 CT3,4 – 24K HS (80mm).
- Localised reinforcements: 1 layer of 450 g/m<sup>2</sup> biaxial fabric, applied along the edges to facilitate demoulding and in the pillar junction area for additional reinforcement.

#### Upper Roof Section and Cover Replacing the Solar Panel

- Lower layer: 1 layer of recycled carbon fibre OCI 1535 R BT300 CT3,4 – 24K HS (80mm).
- Structural core: 5 mm recycled PET panel.
- Upper layer: 1 layer of recycled carbon fibre OCI 1535 R BT300 CT3,4 – 24K HS (80mm).

This structural configuration was designed to optimise load distribution, minimise additional weight resulting from resin absorption in the recycled fibre, and ensure the feasibility of the vacuum infusion manufacturing process.

#### 4.2.2 Inspection and Final Product Evaluation

---

The recycled materials used in the T-Top manufacturing process underwent mechanical testing at the STFI composites laboratory prior to their application in the project. These tests included tensile strength, flexural strength, interlaminar shear strength (ILSS), Young's modulus, and fibre volume content, allowing for a detailed characterisation of the material's behaviour before integration into the demonstrator. However, no structural mechanical tests were conducted on the final T-Top, as structural laminate validation in the nautical industry is based on computational structural models. These models use pre-characterised material data provided by classification societies to assess performance. The final product evaluation focused on

visual inspection, laminate analysis, and resin impregnation verification, ensuring the quality and integrity of the manufacturing process.

### **Inspection Methods Applied**

Visual inspections were carried out at different stages of the manufacturing process to detect potential defects and evaluate the laminate quality. Particular attention was given to the following aspects:

- Surface defects: Detection of porosity, roughness, and vacuum marks.
- Laminate homogeneity: Verification of uniform reinforcement and core distribution.
- Resin impregnation state, with special focus on:
  - Dry areas, caused by irregular reinforcement distribution in certain compacted zones.
  - Over-impregnation, characteristic of non-woven reinforcements, which retain a greater amount of resin.
  - Presence of microbubbles in the laminate, generated by the dispersed fibre structure of the recycled reinforcements.

### **Inspection Results**

Visual analyses confirmed that the vacuum infusion process enabled uniform impregnation across most of the structure. However, certain specific characteristics were observed:

- High resin absorption in the recycled non-woven reinforcement, leading to an increase in the component's total weight.
- Localised microbubble formation, particularly in areas where material compaction was not optimal. This phenomenon is inherent to non-woven reinforcements, whose open structure creates microspaces where resin distribution is not entirely homogeneous.
- Satisfactory surface finish, with good adhesion of the protective coating, enhancing UV resistance, moisture protection, and corrosion resistance.

The evaluation of the T-Top confirmed the feasibility of using recycled carbon fibre in nautical applications, albeit with certain limitations arising from its high resin absorption, lower mechanical properties compared to conventional fabrics, and the less compact structure of the non-woven material. These characteristics necessitated specific adjustments in the manufacturing process, particularly in the laminate configuration, where biaxial fabric reinforcements were applied in critical areas to enhance the component's strength. Additionally, modifications were made to the infusion strategy, implementing an optimised distribution of injection points and the use of specific flow mesh systems to improve material impregnation and minimise the formation of microbubbles.

## ***4.3 Virgin materials product comparison***

---

Within the MC4 project, the objective was to develop both a recycled unidirectional fabric and a non-woven reinforcement from recycled carbon fibre. During the development phase, it was determined that producing a woven unidirectional fabric was not viable due to the characteristics of the recycled fibres. Their fragmented structure and low friction properties led to instability during processing, making it challenging to achieve a structurally coherent woven fabric. As a result, efforts were redirected towards optimizing non-woven reinforcements. Although these present limitations in their mechanical properties, they were stabilized through stitching to enhance their structural integrity and performance, ensuring their suitability for application within the project.

#### **4.3.1 Availability and Development of Recycled Material**

---

During the initial phases of the project, a mat-type material was received but was discarded due to its lack of cohesion and low mechanical strength, making it unsuitable for nautical applications. Subsequently, following technical meetings with Chomarat and STFI, the first stitched reinforcement with polyester, OCI 1505 R BT200 CT3,4 – 12K/1, was supplied. This material was used to manufacture an initial prototype pillar, allowing for the assessment of its processability in the fabrication of a structural T-Top component. These initial tests enabled the adjustment of vacuum infusion parameters and the evaluation of resin impregnation in the recycled reinforcement.

Later, the material OCI 1524 R BT400 CT3 50K HS – (80mm) was received. Its higher density provided greater stiffness but proved excessively thick for the T-Top application, making shaping more difficult and negatively impacting the weight-to-strength ratio of the laminate. Nevertheless, it was used to manufacture various prototypes for project dissemination activities, some of which were requested by other consortium partners, such as Chomarat and STFI.

In the final phase of the project, the material OCI 1535 R BT300 CT3,4 – 24K HS (80mm) was supplied. Drawing on the experience gained from numerous previous internal tests, laminate parameters were optimised, and adjustments were made to the vacuum infusion strategy to mitigate the limitations of the non-woven material. Using this reinforcement, both pillars and the T-Top roof structure were manufactured, consolidating a production process adapted to the specific characteristics of the recycled material.

#### **4.3.2 Key Differences Between Recycled and Virgin Materials**

---

One of the main challenges in integrating recycled carbon fibre developed in the project into the nautical industry lies in the structural configuration differences between this material and conventional virgin fibre fabrics. Composites used in boat manufacturing typically incorporate woven virgin carbon fibre fabrics, which allow for optimised load distribution and greater mechanical efficiency compared to non-woven reinforcements. Unlike woven fabrics, non-woven materials have a disordered and discontinuous fibre structure, which reduces the laminate's ability to withstand mechanical stresses and compromises its efficiency in structural applications.

##### **Structural and Mechanical Differences Between Woven Fabrics and Non-Woven Reinforcements**

Woven fabrics, widely used in naval construction, feature a regular fibre arrangement in a two-dimensional interlaced structure, typically configured as plain weave, twill, or unidirectional (UD) fabric. This structure provides:

- Controlled mechanical load distribution in predefined directions, optimising load transfer within the laminate. Biaxial or multiaxial configurations achieve high strength across multiple directions.
- Higher structural efficiency, as the fibre alignment allows for more effective absorption of tensile and flexural stresses, minimising deformations.
- Precise control of fibre volume fraction, reducing resin uptake and optimising the weight-to-strength ratio of the final component.
- Homogeneous compaction during infusion, minimising defects such as dry spots, porosity, and excessive resin accumulation.

In contrast, recycled non-woven reinforcements have a random and discontinuous fibre arrangement, where filaments do not follow a defined directional pattern. In the materials used in this project, stabilisation was achieved through stitching with polyester thread, providing some cohesion but not resolving the structural limitations inherent to this type of reinforcement.

### Key Limitations of Non-Woven Reinforcements

Non-woven reinforcements, composed of randomly oriented and discontinuous fibres, lack the structured arrangement of woven fabrics. This irregular distribution affects their mechanical performance and processing behaviour, leading to specific limitations in composite applications:

- Non-uniform mechanical load distribution, as random fibre orientation prevents efficient reinforcement in specific directions. Consequently, these materials are not suitable for primary components subjected to high structural loads.
- Lower stiffness and reduced tensile and flexural strength, as the lack of fibre alignment decreases the material's ability to withstand loads applied in a specific direction. For this reason, non-woven reinforcements are generally used as secondary or complementary materials in hybrid laminates, rather than as primary reinforcements in structural applications.
- Higher resin absorption, due to the open structure of the material, which creates voids between fibres, leading to greater resin consumption compared to conventional fabrics. Internal testing showed that the recycled non-woven reinforcement retained between 65.9% and 82.3% more resin than a virgin carbon twill, depending on the number of layers used. This difference, calculated for the same material thickness, increases the final laminate weight without proportional improvements in mechanical properties. Additionally, resin consumption increases with the number of layers and the geometric complexity of the part.

Table 8. Comparison of resin absorption and thickness between virgin twill and recycled non-woven carbon fibre

Material	Weight (g/m <sup>2</sup> )	Final weight (g)	Thickness (mm)	Resin/fibre ratio	Resin increase vs Twill (calculated at the same thickness)
<b>Virgin Twill</b> (MC4-038/24, 3 layers)	416	118	1.35	3.55	-
<b>Recycled Non-Woven</b> (MC4-034/24, 1 layer)	400	172	2.2	5.89	65.9%
<b>Recycled Non-Woven</b> (MC4-035/24, 2 layers)	400	373	4.7	6.47	82.3%

- Increased laminate thickness, as a result of the high resin absorption of the recycled non-woven reinforcement. The excessive resin retention increased the material volume compared to an equivalent laminate in virgin carbon fibre, affecting the weight-to-strength ratio.
- Higher susceptibility to impregnation defects, such as microbubble formation and localised resin accumulation, due to the lack of fibre network continuity, which disrupts uniform resin flow during infusion.
- Difficulties in laminate consolidation, as the non-woven structure creates areas of lower compaction, potentially leading to density gradients in the polymer matrix after curing.
- Increased susceptibility to delamination, as the interlaced fibres can cause stress concentrations in the matrix, promoting interlaminar separation under cyclic loads.
- Low fatigue resistance compared to composites with continuous fibre reinforcements, as repeated loading may induce microcracks in the matrix and lead to progressive loss of cohesion between laminate layers.

### **Adaptations in the Manufacturing Process**

Given the limitations of the recycled material, adjustments were necessary in the production process to optimise laminate quality and mitigate its deficiencies:

- Strategic biaxial fabric reinforcements in critical areas to enhance mechanical strength and reduce the negative effects of random fibre distribution.
- Optimisation of the infusion strategy, adjusting injection point placement and using specific flow mesh configurations to improve impregnation and reduce defects.
- Resin content control, implementing a controlled impregnation protocol to minimise over-absorption and improve process efficiency.

As high resin absorption is the primary limitation of recycled non-woven reinforcement, measures were introduced to regulate impregnation and prevent unnecessary resin accumulation. The strategies tested in this protocol included:

- Pre-compaction of the material ("debulking") using controlled vacuum before infusion, reducing reinforcement porosity and improving resin flow uniformity.
- Progressive vacuum regulation, applying a variable pressure profile during infusion to achieve more controlled impregnation and minimise excessive resin retention.
- Segmented infusion by zones, initiating resin flow in areas with higher resistance to impregnation and controlling its progression using flow barriers.
- Optimised selection of flow meshes, employing lower permeability configurations in areas prone to over-impregnation to slow down resin absorption in those regions.

These adaptations improved laminate quality and optimised resin usage, mitigating the limitations of the recycled non-woven reinforcement as much as possible.

## ***4.4 Economical evaluation***

---

The economic feasibility of the T-Top manufactured with recycled carbon fibre using a vacuum infusion process has been extensively evaluated in comparison with an equivalent T-Top made of glass fibre using manual lamination. The data obtained has been analysed through a detailed life cycle assessment. The results indicate that, while recycled material can offer some cost competitiveness compared to virgin carbon fibre, its mechanical performance remains lower. Additionally, it is still less competitive than glass fibre, which not only has a lower raw material cost but also enables a more efficient manufacturing process.

### **4.4.1 Comparison of Material and Process Costs**

---

The cost analysis considered both the materials used and the efficiency of the manufacturing process. Some key differences include:

#### **Raw Material Cost**

In the T-Top manufacturing process, raw material costs accounted for 24% of the total cost in the circular process, whereas in the equivalent T-Top made from glass fibre using manual lamination, this figure was 12%. This indicates that, although recycled material is less expensive than virgin carbon fibre, it remains significantly more costly than glass fibre. This higher raw material cost, combined with its lower mechanical performance, affects the economic competitiveness of recycled materials compared to conventional alternatives used in the nautical industry.

**Resin Consumption**

One of the most critical factors in the cost analysis was the higher resin consumption of recycled material. According to the collected data, the T-Top manufactured with recycled carbon fibre required 63% more resin than its glass fibre equivalent. This directly impacts the total material cost, as resin constitutes a significant percentage of the final laminate price.

**Manufacturing Process Cost**

The T-Top manufactured with recycled carbon fibre within a circular process resulted in a 9% higher life cycle cost compared to conventional manufacturing using glass fibre. However, due to material recovery and recycling credits, this additional cost was reduced to 6.8%, demonstrating that the implementation of reuse strategies can partially mitigate the economic impact of using recycled materials.

In both approaches, the manufacturing phase represents the highest cost within the product's life cycle, accounting for 72% of the total cost in the circular process, whereas in the conventional process, it represents 87%.

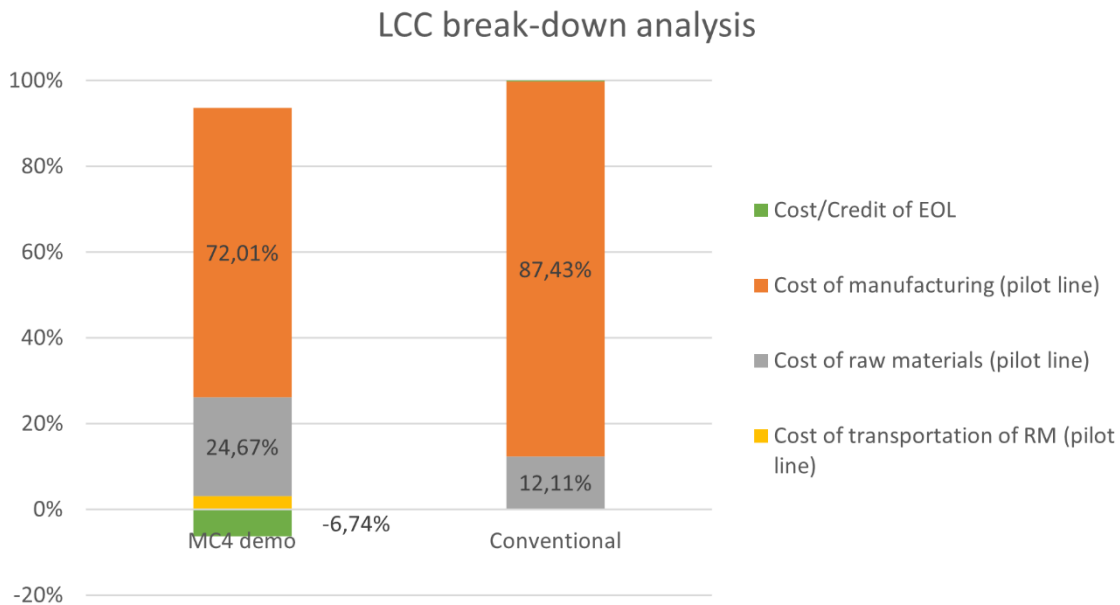


Figure 17. LCC break-down analysis per life cycle stage for MC4 T-top roof and the conventional (iRES Partner)

**3.4.2 Impact on Operational Costs and Process Efficiency – Conclusions**

These results indicate that, while the use of recycled materials can provide certain advantages in terms of waste reduction and end-of-life recycling credits, the manufacturing process remains the key factor in the economic competitiveness of the product. This is particularly due to the necessary process adjustments and higher resin consumption required to compensate for the limitations of the recycled non-woven reinforcement.

Beyond direct material costs, the integration of recycled carbon fibre introduced modifications to the manufacturing process, impacting the economic viability of the project. While replacing manual lamination with vacuum infusion was expected to optimise production efficiency by enabling better compaction and reducing handling times, the lower structural stability of the recycled non-woven material and its higher

resin absorption necessitated additional adjustments, which partially offset the expected time-saving benefits of infusion.

As a result, production time did not decrease as anticipated, and the infusion process did not generate the expected reduction in operational costs. This demonstrates that, although recycled materials can be integrated into composite manufacturing using infusion, process efficiency remains dependent on reinforcement optimisation, which in this case required modifications that ultimately impacted the economic balance of the product.

## ***4.5 Design and manufacturing lessons learnt***

---

The development of the T-Top within the MC4 project has enabled the evaluation of recycled carbon fibre performance in the nautical industry and its integration into advanced manufacturing processes. Although the available material was limited to a stitched non-woven reinforcement and a recycled unidirectional fabric was not developed, the manufacturing process demonstrated that a high-quality final product could still be achieved, with an optimal finish and a production process adapted to its specific characteristics.

The key learnings from this experience are outlined below:

### **Strengths of Recycled Material**

- **Lower environmental impact and process circularity:**

The use of recycled carbon fibre contributes to reducing industrial waste and dependency on virgin raw materials, aligning with the sustainability and emission reduction goals of the sector.

Additionally, the ability to reintroduce offcuts into new applications reinforces its potential within circular economy strategies.

- **Viability in vacuum infusion processes:**

Despite differences from conventional fabrics, the recycled material was successfully processed through vacuum infusion, achieving good laminate quality and a suitable surface finish for nautical applications.

- **Applicability in low structural demand or sustainability-focused applications:**

In components where mechanical load is not a critical factor, such as accessories, fairings, or secondary reinforcements, recycled material offers a viable alternative to reduce the environmental impact of composite manufacturing. Although its higher weight limits its use in primary high-performance structures, it remains relevant in sectors where sustainability plays a key role.

### **Identified Weaknesses and Limitations**

- **Lower mechanical properties compared to conventional fabrics:**

The lack of controlled fibre orientation reduces laminate stiffness and strength, limiting its use in structural elements subjected to high loads.

- **Higher resin absorption and increased weight:**

The open structure of non-woven reinforcements results in significantly higher resin consumption compared to woven fabrics, increasing the final weight of the parts and affecting viability in weight-sensitive sectors, such as nautical applications. This also reduces competitiveness compared to traditional alternatives like glass fibre or virgin carbon fabrics.

- **Requirement for additional reinforcements and process adjustments:**

To compensate for mechanical deficiencies, it was necessary to incorporate virgin biaxial carbon fabric in critical areas, as well as modifications to the infusion strategy. These adaptations impacted both process efficiency and the overall economic balance of the final product.

#### **4.5.1 Potential Applications in the Nautical Industry**

---

The study conducted within the MC4 project has demonstrated that, although recycled carbon fibre is not suitable for primary structural components in boats, its integration into the nautical industry is feasible in

hybrid applications or in products where sustainability is a key criterion. In sectors such as inland water vessels, lake boats, or projects with environmental certifications, recycled material presents a viable alternative, offering the advantage of reducing environmental impact while remaining compatible with industrial processes such as vacuum infusion. In conclusion, its incorporation into a sustainability and circular economy approach expands its potential applications within the nautical industry and other environmentally driven sectors. The project has validated that, with the necessary adaptations, it is possible to manufacture high-quality products using recycled materials, optimising their processing and maximising their potential within a more efficient production model.



### ***5.3 Virgin materials product comparison***

---

Materials are the same as described in 3.3.

### ***5.4 Design and manufacturing lessons learnt***

---

The pedestal base presented greater challenges due to the complexity of its geometry. Although the nonwoven material had a stitching pattern to supply some consistency and direction to the carbon fiber, it was not ideal for parts with intricate shapes like the pedestal. The chain-tricot stitching used by Chomarat made it difficult for the textile to conform to the mould, which impacted the subsequent compression step with the silicone membrane. In contrast, the same part was manufactured using a commercially available recycled carbon fibre nonwoven with chain stitching (benchmark), which adapted better to the mould, resulting in better compression and aesthetic properties.

As a general conclusion the prepreg developed based on recycled reinforcement provided by Chomarat is suited for manufacturing simple, flat components. However, the use of this new material for production of parts with complex geometries is limited.

## 6. AEROSPACE COMPONENTS MADE FROM RECYCLED MATERIALS

### 6.1 Recycling and manufacturing process description

#### 6.1.1 Aerospace use-case

This study focuses on demonstrating the manufacturing feasibility of aerospace parts from reused materials developed within MC4 project. For this purpose, a semi-structural part of the Airbus A380 was selected as a use-case: the leading-edge front rib. This part is placed on the leading-edge of the horizontal stabilizer,

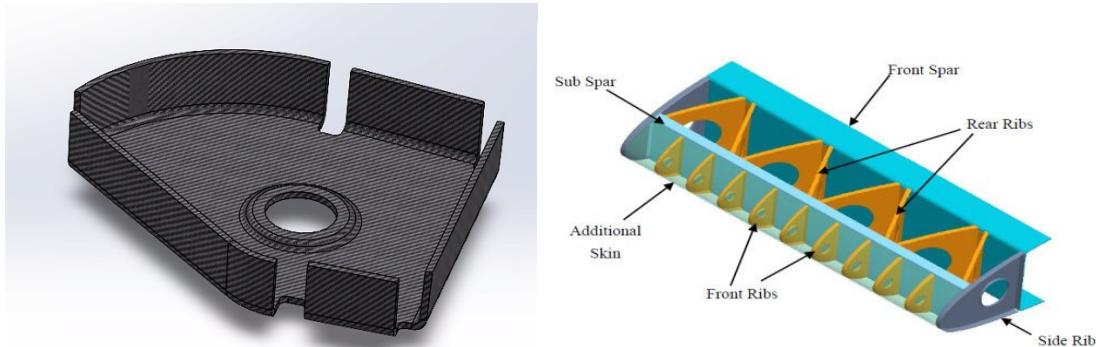


Figure 20: Rib geometry placed on the leading edge

as shown in Figure 20. The stabilizer is a fixed aerodynamic surface designed to enhance the aircraft's stability and maintain a straight and level flight. The vertical stabilizer plays a crucial role in counteracting unwanted lateral movements, effectively preventing excessive side-to-side, or yawing, motion of the aircraft's nose. A key aspect of this study is the utilization of reused and calendered material, which undergoes a controlled thickness reduction process to optimize its mechanical properties and ensure uniformity.

#### 6.1.2 Scrap transformation process

This research starts with the stringers manufacturing for the Airbus A320, and with the reusing of its scrap. Initially, a flat panel laminate with a predefined layout is produced to cut the stringer preforms. Once the preforms are cut, the remaining waste from the flat panel laminate is processed to obtain homogeneous rectangular strips with a width of 20 mm and a thickness of approximately 2.2 mm. It is important to highlight that this waste accounts for 20% of the total raw material used for each flat panel laminate (Figure 21: Typical view of the off-cuts generated by the ATL). Subsequently, these strips undergo calendering technology to reduce their thickness from 2.2 mm to 1 mm, with a tolerance of  $\pm 0.2$  mm.

The calendering process aims to reduce the thickness variations in carbon fibre (CF) scrap and align fibres predominantly in the  $0^\circ$  direction, which enhances material performance. This process follows an initial cutting step where scrap is prepared into manageable strips. These strips are processed through a calendering machine equipped with compacting rollers. After sorting and classifying the prepreg scrap and cutting it to the desired strip widths, the calendering process begins. This stage focuses on reducing the thickness of the

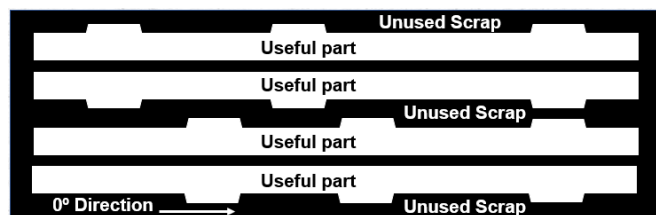


Figure 21: Typical view of the off-cuts generated by the ATL

After sorting and classifying the prepreg scrap and cutting it to the desired strip widths, the calendering process begins. This stage focuses on reducing the thickness of the

material from 2mm to approximately 1 mm. The calendaring process involves feeding the prepreg strips into a pre-heated calendaring machine, where the roller gap is gradually adjusted with each pass to achieve the target thickness (Figure 22).



Figure 22: Calendaring method considering scrap as raw material, strip compaction and strip results

The bar chart below (Figure 23) illustrates the relationship between the width of CF prepreg strips and their final thickness after the calendaring process, using the same number of calendaring steps. As the graph shows, wider strips consistently result in greater final thickness compared to narrower ones, which aligns with the technical explanation previously discussed.

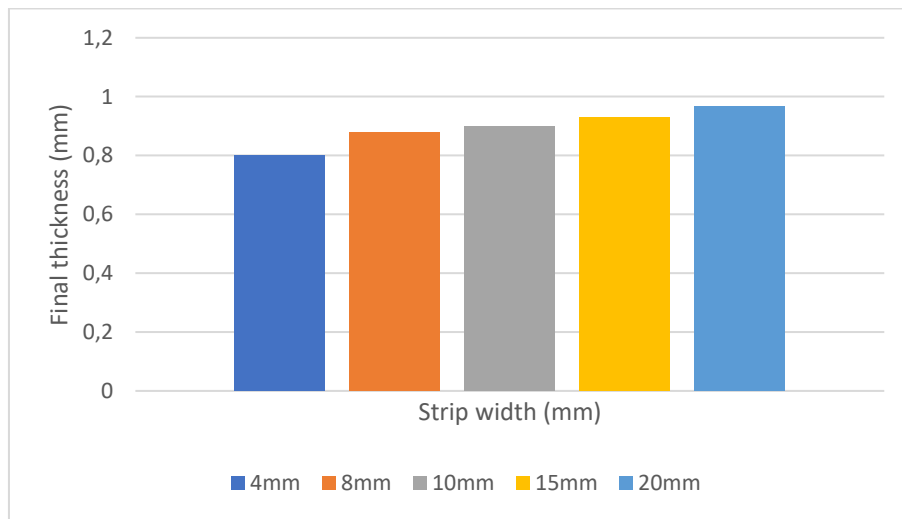


Figure 23: Evolution of final thickness with increasing width and same number of steps

The increase in final thickness with strip width is evident from the trend in the graph, where strips of 4 mm width achieve the lowest final thickness, while strips of 20 mm width retain the highest. This directly correlates to the distribution of pressure across the rollers: the wider the strip, the more the pressure is diluted over the surface, reducing the compaction efficiency. Additionally, the limited lateral flow of material in wider strips and their greater inherent stiffness contribute to the observed trend.

In this process, the fibre continuity and its length is crucial for ensuring uniform mechanical properties. If the strip width is too narrow, the alignment and continuity of fibre orientation within the laminate can be compromised, potentially leading to localized variations in stiffness, strength, and overall material performance. A narrower strip may introduce discontinuities or gaps between adjacent layers, affecting load transfer efficiency and structural integrity. Therefore, the 20 mm width was chosen to maintain a consistent and homogeneous laminate structure.

As a summary, Figure 23 serves as a clear visualization of these effects, reinforcing the importance of optimizing strip width during the calendaring process to achieve the desired thickness reduction

### 6.1.3 Use-case manufacturing description

Regarding the leading-edge rib manufacturing, the hot-press technology was selected to process it using this reused material because the strip thickness is much higher in comparison with conventional aerospace prepreg plies. Considerable compaction pressure is needed to reach the required tolerance of the thickness part. The sequence of the hot-press technology using the reused material is as shown in Figure 24.



Figure 24: Manufacturing methodology for hot-press technology using reused material

In the Figure 25, it is possible to observe the whole process of the curing press cycle, obtained after the manufacturing of the demonstrators. It has been obtained by placing a thermocouple between the laminated layers of carbon. The cycle starts at room temperature and rapidly ascends to a temperature of around 180 °C in 25 minutes. The curing cycle is set to 2 hours at 180 °C. The key is for the CF to first reach 80 °C to ensure the material's malleability and moldability. Then, a compaction pressure of around 8 bar is applied. After that, the temperature of the CF needs to go up to 180 °C, to make sure that the curing process starts. These conditions need to remain constant for a set duration, 2h in this case, allowing the material to cure and create a strong bond, obtaining a uniform curing. Finally, the pressure is gradually released and proceed to hot demolding.

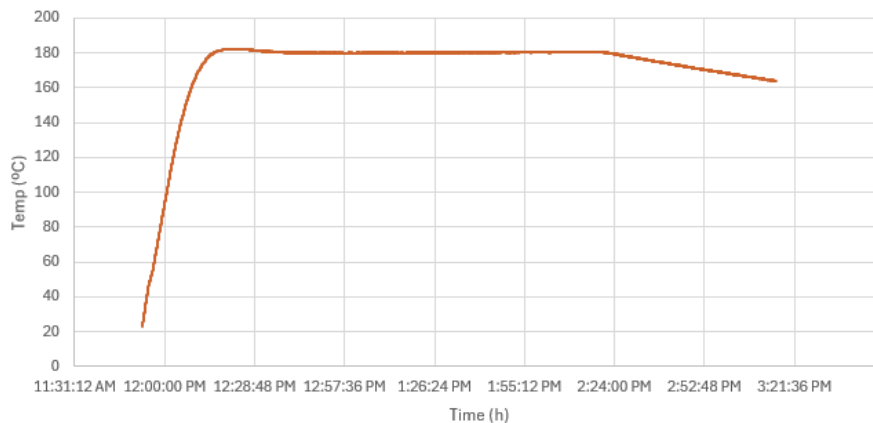


Figure 25: Curing press cycle

### 6.1.4 Full circular process chain

The full circular process chain of the production of the leading-edge rib use-case can be observed in Figure 26. It consists of several steps, starting from waste production and ending up in manufacturing reused

aerospace products. Four main steps have been identified, plus the end user, allowing for a circular, repeatable process.

Initially, the waste generators are responsible for ensuring that waste is provided in an optimal condition for reprocessing. Currently, prepreg scrap is discarded directly into a container, resulting in a compacted mass of material. To improve waste management, the disposal process should be adjusted to maintain the scrap as aligned and flat as possible. In this case, this role is represented by aerospace component manufacturers, either OEMs or Tier 1 companies. In a second step, the waste management company should look after the prepreg scrap, ensuring proper collection, followed by accurate cutting and storage. A specialized waste management organization should handle it due to the specific requirements for handling, transport, and storage, particularly the need for frozen conservation.

In further processes, two actors not currently present in the chain are required. The first one is transformation process responsible, in charge of the calendaring process and the flat panel production from calendared strips. At this stage, panels can be supplied to the composite parts manufacturer for using as raw material for the hot-press technology. Lastly, the composite part manufacturers, as the end users, should apply the hot-press technology for the manufacturing of the reused material. The main reason of the selection of this process was due to the higher thickness of the strips compared to the conventional aerospace prepreg plies

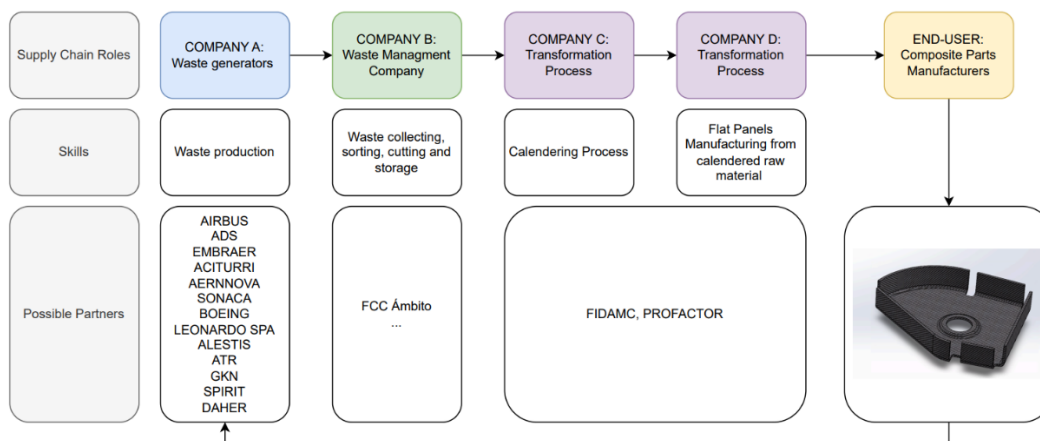


Figure 26: Overview of value chain approach for the reused material production focused on leading-edge rib application

## 6.2 Technical specifications assessment

This section of the deliverable will provide a detailed analysis of the various fabrication methods studied to carry out the leading-edge rib use-case. Four technology demonstrators have been manufactured using both virgin carbon fibre (Demonstrator 0) and different manufacturing techniques with the recycled carbon fibre strips (Demonstrator 1-3).

### 6.2.1 Demonstrator 0: Leading-edge rib use-case developed by RTM technology (baseline)

The main objective of manufacturing the technology Demonstrator 0 using the RTM (Resin Transfer Molding) technology is to serve as a baseline (Figure 27). This demonstrator serves as a reference for comparing results as the physicochemical and mechanical properties, manufacturability, and cost-effectiveness of the process compared to other fabrication methods.

RTM is a manufacturing process in which a liquid thermoset resin is injected into a closed mould containing a fibre preform. This method allows to produce complex composite structures with high fibre content and precise dimensional control. The process begins by placing a dry fibre reinforcement, carbon fibre in this case, into a mould cavity. Once the mould is closed, resin is introduced under pressure, permeating the fibre preform and filling the mould. After the resin cures, the composite part is finished. RTM offers advantages such as improved surface finish, reduced void content, and the ability to incorporate complex geometries and integrated components. However, it requires careful control of processing parameters, including resin viscosity, injection pressure, and mould temperature, to ensure complete impregnation of the fibres.

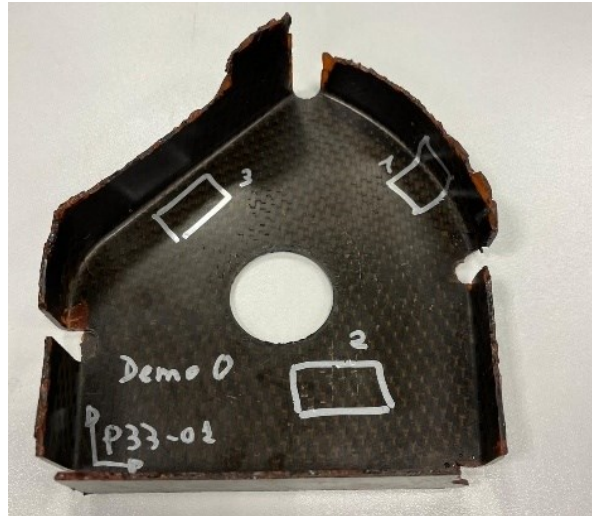


Figure 27: Demonstrator 0 manufactured using RTM technology (baseline)

### 6.2.2 Demonstrator 1: Leading-edge rib use-case developed by hand lay-up & vacuum bag

The main objective of manufacturing the Demonstrator 1 by hand lay-up and vacuum bag is to study the influence of the compaction pressure on the material quality. In this case, the compaction pressure applied is only the vacuum pressure whereas in the following case, Demonstrator 2 (detailed in the chapter 6.2.3), a compaction pressure provided by hot-press (around 8 bar) was considered. Figure 28 presents demonstrator 1 result.

The hand layup and vacuum bag process begins by heating each strip with an industrial dryer to increase flexibility, allowing it to conform to the convex tool. Once the preform is manually completed, the release film and vacuum bag are applied. Vacuum pressure is then applied to ensure the preform fully conforms to the mould shape. Finally, the curing cycle is carried out for two hours at 180°C.



Figure 28: Demonstrator 1 manufactured by hand lay-up & vacuum bag

### 6.2.3 Demonstrator 2: Leading-edge rib use-case developed by hot-press process and 3 plies

The primary objective of manufacturing Demonstrator 2 using the hot-press process was to assess the impact of high compaction pressure on the quality of the composite material. This demonstrator was

manufactured from three plies with a  $0^\circ$ ,  $90^\circ$ ,  $0^\circ$  layup. By using this configuration, also an optimal number of plies could be determined for the demonstrator.

The hot-press process begins with the arrangement of calendered composite strips with a slight overlap of 2-3mm to facilitate bonding during the consolidation phase (the process of fusing the strips together).

Heat of  $60^\circ\text{C}$  and vacuum pressure were applied for 60 minutes. This promotes adhesion, forming a flat panel that is then cut to match the dimensions of the two-part mould, which consists of a male component made of aluminium and a female component made of steel.



Figure 29: Demonstrator 2 after hot-press process

The first observation of Figure 29 is the material excess outside the tool cavity. Also, the extra material generates excessive pressure in the radii (delineated by red circles), making the demoulding severely laborious. In conclusion, the manufacturing of this component using 3 plies of calendered material does not represent a viable option, both due to the loss of resin and manufacturing issues. The figure below (Figure 30) shows the result for demonstrator 2.



Figure 30: Demonstrator 2 manufactured using hot press process

#### 6.2.4 Demonstrator 3: Leading-edge rib use-case developed by hot-press process and 2 plies

The primary objective in manufacturing demonstrator 3 using, again, the hot-press process was to minimize material waste during preform fabrication by reducing the number of plies in the laminate. As noted in the analysis of demonstrator 2, a layup formed by three plies presented manufacturing challenges. For this demonstrator, the preform was fabricated using only two plies of calendered material, compared to the three plies used in Demonstrator 2. The hot-press process followed the same arrangement of calendered strips as demonstrator 2, with the key difference being the reduction from three plies to two.



Figure 31: Demonstrator 3 manufactured using hot-press process and 2 plies

Visual inspection revealed that demonstrator 3 exhibits higher quality than demonstrator 2, with fewer dry spots and areas of resin deficiency (see Figure 32). Areas marked in red represent dry spots (i. e. areas where there is not enough resin impregnation after the hot-press process), that could lead to reduced mechanical properties, increased porosity, delamination and inconsistent performance.



Figure 32: Comparison of dry spots and resin deficiency on the surface of Demonstrator 2 (3 plies, left) and Demonstrator 3 (2 plies,

### 6.2.5 Characterization Results: Fibre Volume Fraction (FVF) & Void Content

The figure shown below (Figure 33Figure. 34) illustrates a comparison of fibre volume fraction (FVF) values for various demonstrators, including data obtained from flat panel samples. The flat panel samples represent the baseline FVF before shaping and serve as a reference point. The FVF values for all demonstrators shown in the figure, except for Demonstrator 3, exceed the nominal fibre volume fraction of 57.4%, reaching approximately 65%. This increase in FVF for most demonstrators suggests resin loss during the calendaring process. This resin loss likely contributes to the formation of dry spots and areas of resin deficiency observed on the demonstrator surfaces, as stated before. Specifically, the calendaring process, which involves compacting the material, may have expelled excess resin.

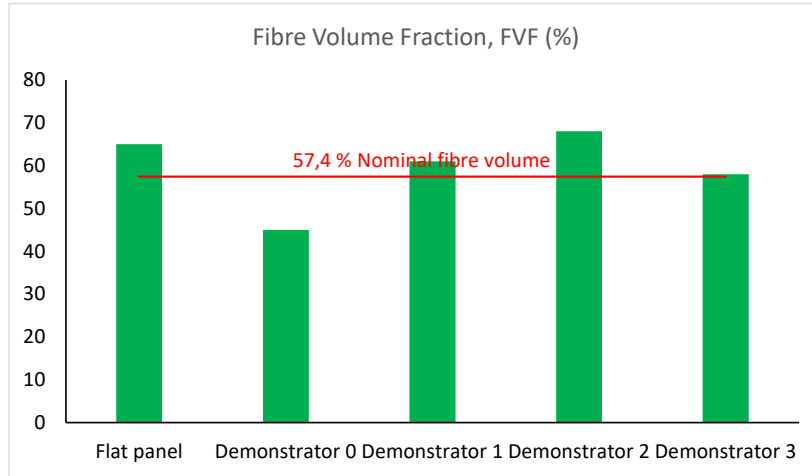


Figure 33: Comparison of FVF between demonstrators

Void content (the percentage of empty space within the material) was measured for each demonstrator, showing that Demonstrator 0 meets the aerospace standard of <2% void content. However, Demonstrators 1 and 2 show higher levels of 10% and 4%, respectively, as could be inferred due to the resin loss. While the hot-press process reduces voids through compaction, Demonstrator 3 only marginally complies with the 2% limit, while the void content in the other reused material demonstrators would render the material unsuitable for the intended application. This indicates a need to refine the manufacturing process, addressing resin loss as a key factor influencing void formation (see Figure. 34).

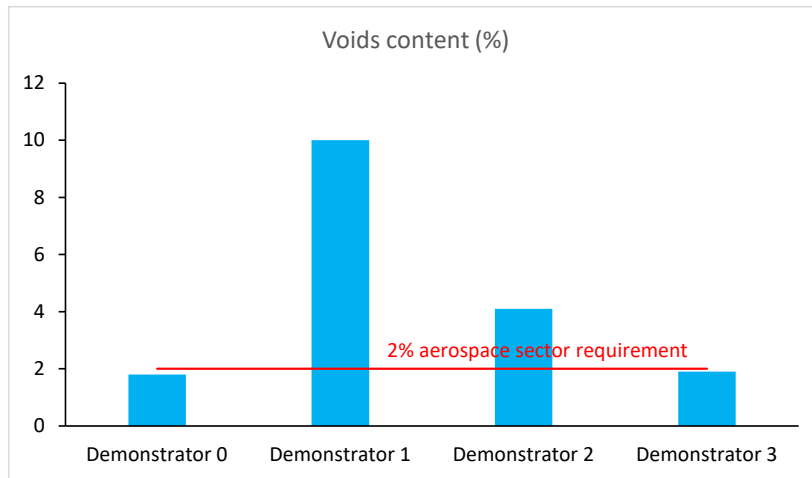


Figure. 34: Comparison of voids content between demonstrators

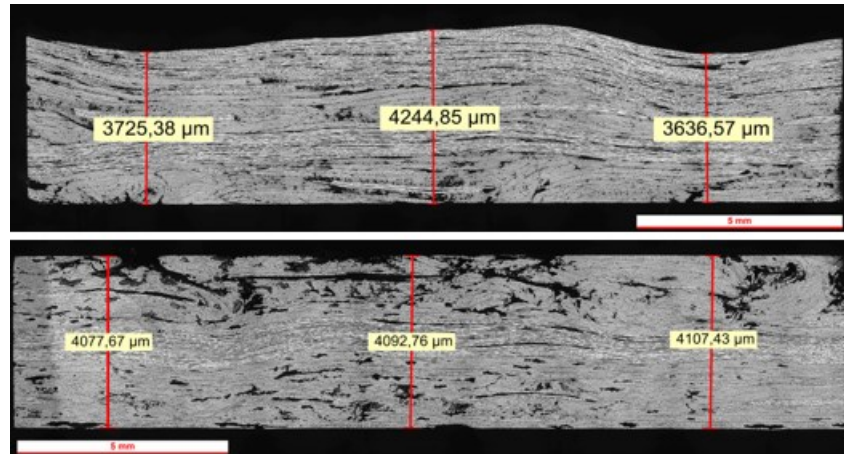


Figure 35: Micrograph analysis for void magnitude and shaping for Demonstrator 1 (up) and Demonstrator 2 (down)

As shown in the figure above (Figure 35), in the case of the Demonstrator 1, a significant thickness variability can be observed. Therefore, it can be concluded that calendered material requires high compaction pressure, due to the high thickness per ply. Many large size voids, with inconsistent shapes are also noted. Regarding Demonstrator 2, less voids are found, although a more severe lack of resin is present. In this case, the layup leads to an excess of compaction and thus, resin is forced out from the demonstrator. On the other hand, the thickness is very uniform due to the rigid metallic tooling.

### 6.3 Virgin materials product comparison

The following table (Table 9) details the thermal, physical-chemical, and mechanical characteristics of the new reused material developed within the MC4 project. These properties, determined using aerospace standard testing methods, are essential for evaluating the material's performance and ensuring it meets application requirements. Key properties include the glass transition temperature ( $T_g$ , critical for thermal stability), fibre volume fraction (FVF, directly influencing mechanical performance), and tensile and compressive properties (Young's Modulus, strength, and elongation at break) in both  $0^\circ$  and  $90^\circ$  fibre orientations, providing a complete picture of the material's mechanical response.

Table 9. Properties of uncured reused material developed within MC4 project

	Properties (unit)	Values
Thermal	$T_g$ (C)	248.85
Physical - chemical	FVF (%)	64.5
Tensile $0^\circ$	Young Modulus (GPa)	77
	Strength (MPa)	480
	Elongation at break (%)	0.6
Compression $0^\circ$	Young Modulus (GPa)	62
	Strength (MPa)	673
	Elongation at break (%)	1.8

Tensile 90°	Young Modulus (GPa)	27
	Strength (MPa)	82
	Elongation at break (%)	0.2
Compression 90°	Young Modulus (GPa)	28
	Strength (MPa)	322
	Elongation at break (%)	0.8

One key parameter is the FVF, which is reported as 64.5%. 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 calendering process, as stated in the accompanying text. The tackiness of the resin leads to its adhesion to the calendering 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.

Figure 36 compares the mechanical properties of uncured, reused material from the MC4 project with a baseline material, consisting of the same carbon fibre and resin system but using virgin fibres. Both materials were tested under tensile and compressive loading at 0° and 90° fibre orientations. The graphs depict the elastic modulus (E) in GPa and mechanical strength in MPa.

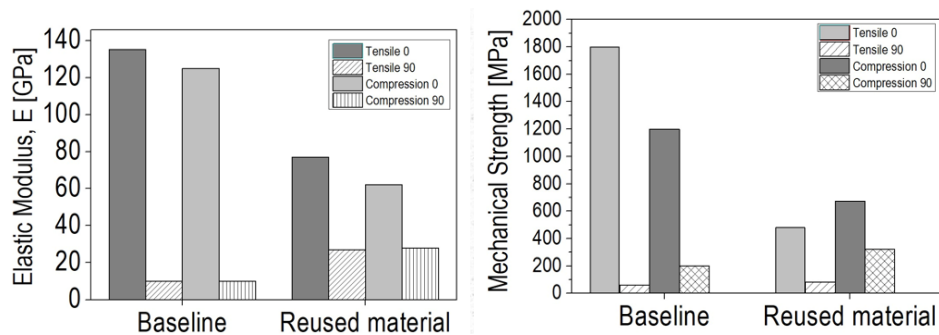


Figure 36: Mechanical properties of the reused material in comparison with baseline

### 6.3.1 Elastic Modulus Analysis

The first graph on the left in Figure 36 displays the elastic modulus (E) in GPa for both the baseline and reused materials. The baseline material exhibits a significantly higher modulus in tensile 0° and compression 0° directions than the reused material, 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.

### 6.3.2 Mechanical Strength Analysis

The second graph on the right in Figure 36 presents the mechanical strength (MPa) under the same loading conditions. The baseline material demonstrates superior strength, particularly in the tensile 0° direction than reused material, 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.

Overall, these results indicate that the reused material undergoes a notable redistribution of mechanical properties. The reduction in 0° tensile and compressive properties suggests potential fibre misalignment or resin degradation, while the increase in 90° tensile and compressive performance indicates improved behaviour in the transverse direction. This shift in properties could be attributed to changes in fibre volume fraction, resin loss, or modifications in fibre-matrix interactions due to the reprocessing method used in the MC4 project.

## ***6.4 Economical evaluation***

---

A significant amount of CFRP residue is generated during the production of aeronautical composite parts. With a buy-to-fly ratio often reaching 1.4:1, up to 40% of the initial material is lost due to cutting, pattern trimming, manufacturing errors, and other factors. Uncured prepreg accounts for 60-70% of this waste, leading to high disposal expenses because it is classified as special waste (due to its potential hazard and difficult disposal) and incurs environmental penalties (around €50/kg). Furthermore, EU waste management policies prioritize reducing environmental impact and fostering resource efficiency by treating waste as a potential resource.

To assess the cost of the manufactured component (leading-edge front rib shown in Figure 20), data on labour and production capacity were considered for both the circular and conventional manufacturing processes. Initial estimates for the circular process were three production cycles per week, with each cycle producing 15 parts. The conventional process was reported to operate at five cycles per week, also with a 15-part output per cycle. Alternative tooling and facility arrangements could increase the circular process's output to two cycles per day. The life cycle cost (LCC) analysis evaluates the circular process under two scenarios: "MC4 demo" representing the current three cycles per week, and "MC4 demo (improved productivity)" reflecting the potential of two additional cycles per day. For the improved productivity scenario, a conservative approach was considered, aligning the circular process's production rate with the conventional process's five cycles per week for a consistent baseline comparison.

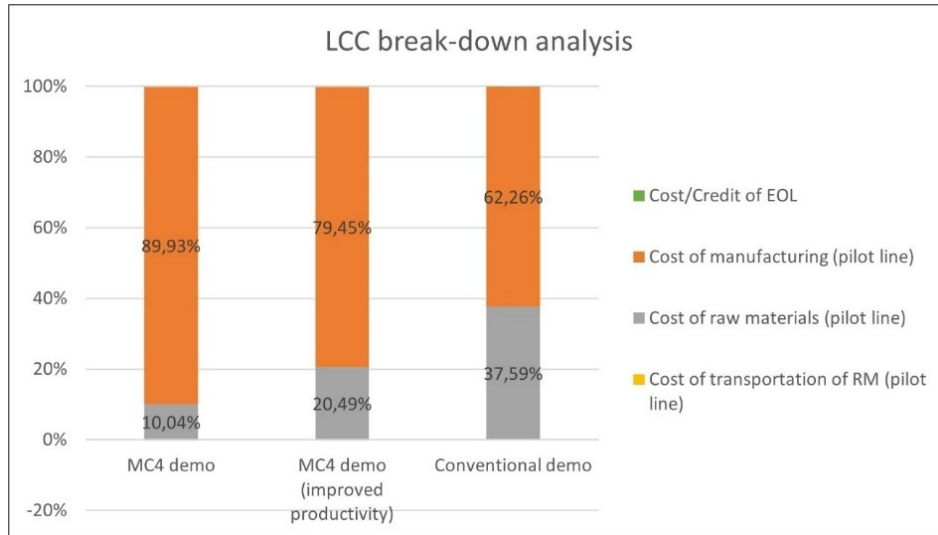


Figure 37: LCC break-down analysis

In the circular process, 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 conventional demonstration, 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.

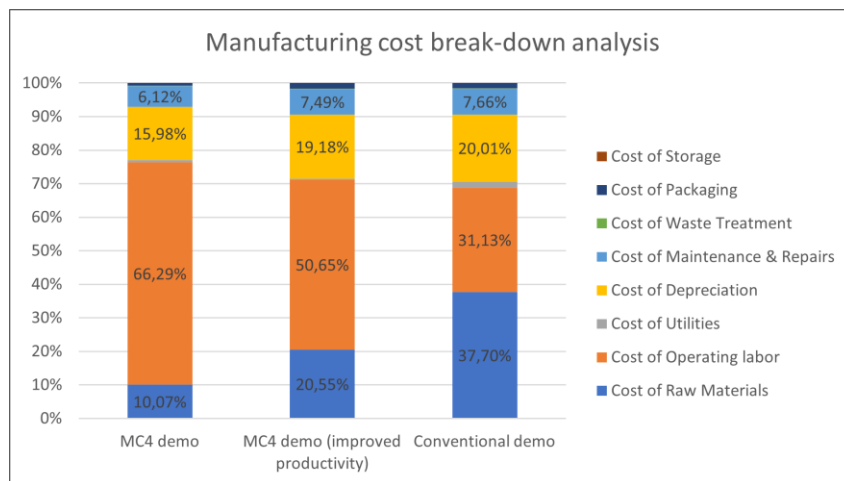


Figure 38: Manufacturing cost break-down analysis

Focusing on the manufacturing phase (Figure 38 above) where raw material costs are included in the calculations, the breakdown analysis reveals that labour is the dominant cost factor, contributing 66% to the total manufacturing cost (reduced to 50% in the improved productivity scenario). Depreciation cost, that take into account the machinery investments, is the second-largest cost category, accounting for 16% (rising to 19% for the alternative scenario). Raw materials cost comes in third contributing 6% and 7,5% for the base and alternative scenario respectively. In the conventional demo, raw materials and depreciation are the main cost factors with 38% and 31% contribution respectively. Depreciation represents a significant cost, accounting for 20% of the final cost.

The comparative analysis in Figure 40, using normalized values, shows that under the operational parameters applied during the manufacturing of the MC4 demo, the life cycle cost (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.

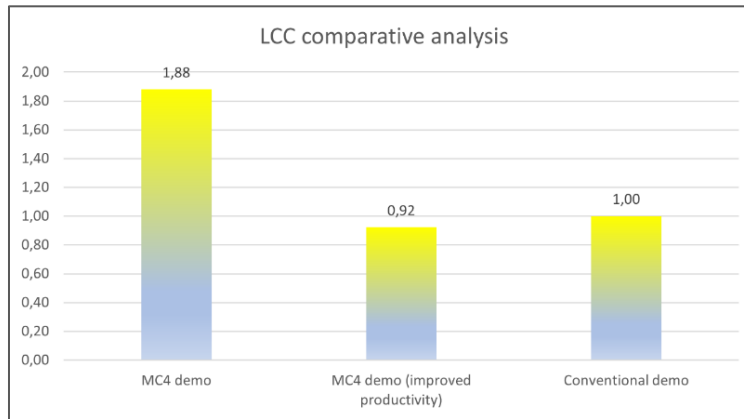


Figure 39: LCC comparative analysis

## 6.5 Design and manufacturing lessons learnt

A key advantage of using reclaimed prepreg is the significant cost reduction achieved in manufacturing. Reusing this material optimizes resource utilization, minimizes raw material waste, and lowers overall production costs without substantially compromising component mechanical performance. Furthermore, the modified material properties can be advantageous in applications where high 0° strength is not critical, enhancing the process's economic viability.

Despite the economic benefits, the process presents several critical challenges. First, strict monitoring of exposure times is required, as the reused material is prepreg and therefore highly sensitive to temperature, humidity, and aging effects. Failure to control these parameters could result in material degradation, leading to suboptimal mechanical and physicochemical properties. Moreover, the management of scrap material must be highly meticulous, ensuring that only viable material is reused to maintain consistency and reliability in manufacturing. 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.

Industrial-scale implementation of this process faces two key challenges. First, managing the CFRP prepreg scrap requires specialized handling by waste management companies (as illustrated in Figure 26). This includes collection, sorting, cutting, and storage, notably the need for freezer storage to maintain the uncured prepreg's properties. These specialized waste management companies must adapt their facilities to meet these specific storage requirements, including investing in appropriate freezer capacity and handling equipment. Second, securing an enough volume of reclaimed CFRP prepreg to justify investment in the new calendaring technology is crucial. This requires the collaboration with major aerospace companies like AIRBUS, EMBRAER, LEONARDO SpA and BOEING, as well as their Tier 1 suppliers such as AERNNOVA, ACITURRI and SONACA, to establish a reliable supply of scrap material.

Regarding the manufacturing process, one of the fundamental conclusions learnt during the project is the minimum thickness limitation imposed by the calendaring process. It has been determined that the thickness of the calendered material cannot be reduced below 1 mm due to the structural requirements of the laminating process. 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.

## **7. SPORT EQUIPMENT MADE FROM RECYCLED MATERIALS**

### ***7.1 Recycling and manufacturing process description***

---

The MC4 project aims at developing new processes to recycle composite materials. It is split into the recycling of both carbon and glass fibre in the short and long term. The kayak and paddle were developed in the context of long-term recycling of glass fibre components. To demonstrate the feasibility of this technique, it was important to develop both the part to be recycled and the recycled part. Indeed, the use of vitrimer resin allows, in this case, a reforming into a different geometry from an existing part to give it a second life. The main advantage of this technique is that the reformed part exhibits mechanical characteristics very close to the original part, thanks notably to the preservation of the fibres. In fact, here the fibres are neither damaged nor reduced in size during the reforming process, offering a high-quality recycling solution at a lower cost. Fibre-matrix separation processes also provide recycling of fibres while maintaining good mechanical properties, but they are far too costly to implement in the case of glass fibre, where the recycled fibre could end up being more expensive than virgin fibre. Therefore, the use of vitrimer resin is the ideal solution to create high-performance recycled glass fibre parts while being economically viable.

The choice of parts to be developed with the use of vitrimer resin was focused on sporting equipment, a field where glass fibre is widely used. It was therefore decided to develop a full-scale kayak made from glass fibre and vitrimer resin, and then to create paddles from preforms directly cut from the kayak.

The kayak is manufactured using the infusion process, which involves stacking various layers of dry reinforcements in a rigid mold and placing the whole assembly under vacuum using a sealed membrane. The entire stack is impregnated by the migration of resin through a stack of peripherals made up of peel plies, drainage mesh, and vacuum bags. The sealing is achieved using a tacky tape. Resin arrival and suction are ensured through various accessories: hoses, spiral hoses, fittings, connectors, etc. This process allows for a higher fibre volume fraction than wet layup (60% compared to 40% in wet layup) and provides better operator protection (fewer VOCs). This method is particularly used for the manufacture of large parts, which is ideal for the kayak, which measures about 4 meters in length.

The epoxy resin, diluent, and hardener mixture that form the vitrimer is infused at a temperature of 60°C to achieve a low enough viscosity for the infusion process. Once the infusion is complete, the mold is heated to 130°C for 1 hour and 30 minutes for curing, then to 150°C for 1 hour for post-curing.

Once the kayak is finished, the preforms for the fabrication of the paddle are cut from the hull and deck using an angle grinder. If the piece was previously painted, as is the case with the kayak, a sanding step is essential to remove any paint. Thermoforming then consists of heating the preform to soften its matrix, followed by shaping it into its final form by pressing it into a mold under a press. The material temperature is raised to 180°C and held for 10 minutes at 60 bars. The cooling of the preform is then realized under the same pressure to prevent any deformation, such as spring back. The laminate of the reformed piece remains identical to the original piece. However, it is possible to stack multiple preforms during thermoforming by adding a vitrimer adhesive. This way, the thickness of the reformed piece can be adjusted to ensure its mechanical properties. A final trimming is done to obtain the finished part.

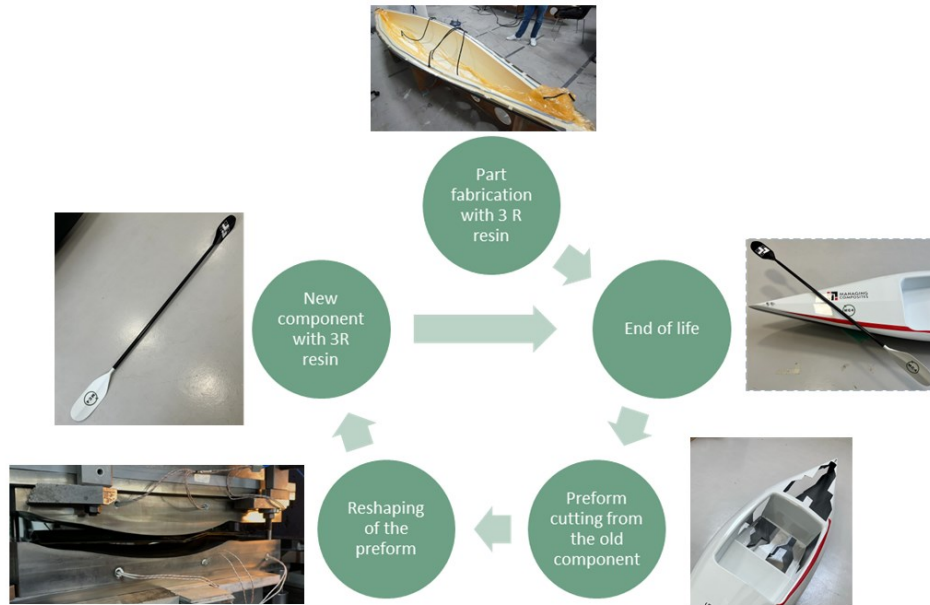


Figure 40. Flow chart diagram of reshaping 3R resin component

## 7.2 Technical specifications assessment

### 7.2.1 Kayak

#### Mechanical performance validation

The laminate sequence of the kayak was defined to ensure proper mechanical strength. The simulation of the kayak was performed in which the load case was representing the weight of a person of 150 kg sitting down on a slightly rearward position from the center of the kayak as it is represented in the figure below. The worst-case scenario was selected with 2 fixed points at the ends of the hull of the kayak.

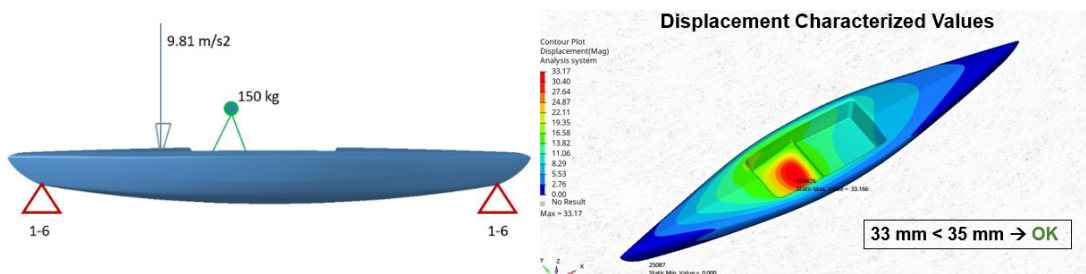


Figure 41. Load case and results of kayak simulation

The laminated below was thus validated by this numerical simulation, ensuring that the maximum displacement and maximum stress do not lead to any rupture of the material. It is worth noting that the mechanical properties used for the simulation come from mechanical tests conducted by CIDETEC on samples infused with the same glass fibre and vitrimer resin.

Table 10. Laminated sequence of the kayak

PLY	MATERIAL	DIRECTION
1	G-Weave 360P_ MC4-F21 0.32T	0/90°
2	G-Weave 360P_ MC4-F21 0.32T	±45°
3	G-Weave 360P_ MC4-F21 0.32T	0/90°
4	G-Weave 360P_ MC4-F21 0.32T	±45°
5	G-Weave 360P_ MC4-F21 0.32T	0/90°
	<b>TOTAL THICKNESS</b>	<b>1.6 mm</b>

**Ergonomic**

The kayak was developed with the average person’s use in mind. To achieve this, CAD tools are used to properly size the seating inside the kayak. In addition, adjustable footrests are added to accommodate a wide range of users.

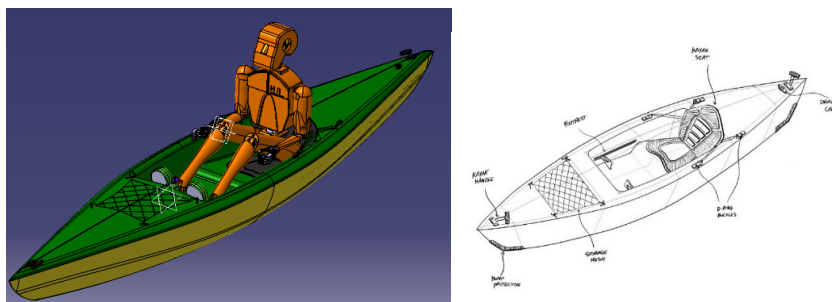


Figure 42. Use of dummy to find ergonomic on the kayak (left) and sketch with hardware (right)

In addition to the hull and deck, the finished kayak includes a series of components to ensure proper functionality. These components are commercially available parts that have been purchased, measured, and then integrated into the design. Among these components, there are handles on each side of the kayak to allow for carrying it between two people; a drainage cap to remove any water that may infiltrate the kayak in case of poor sealing; supports to accommodate a seat and storage nets; and finally, adjustable footrests. The kayak thus has all the necessary features to be directly used by the user.

**Tightness**

The kayak is made up of two main parts: the hull and the deck. The waterproofing is ensured by the union of these two components. The assembly is done using an adhesive that provides both structural bonding and perfect waterproofing for the kayak. The adhesive is applied to the entire flange of the deck to make internal contact with the hull.

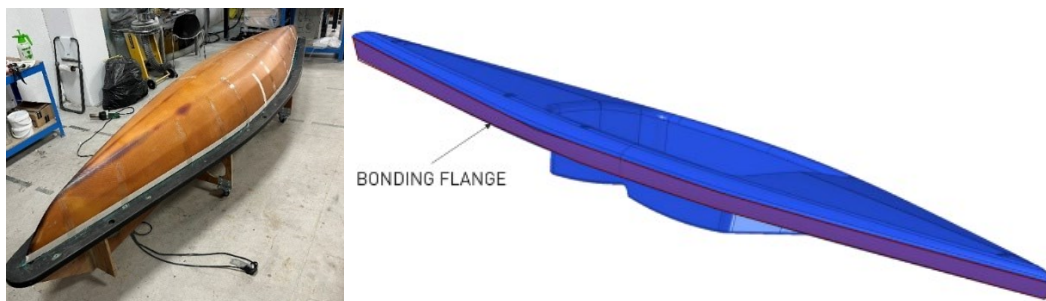


Figure 43. Kayak during assembly (left) bonding flange (right)

It is also essential to ensure the water tightness at the level of the threaded inserts that serve as attachments for the different elements of the kayak. To do this, blind threaded inserts (rivet nuts) are installed with adhesive to prevent any water infiltration at this level.

### Preform extraction for recyclability

One of the key benefits of developing the kayak with 3R resin is the ability to give it a second life. It is essential to consider this aspect in the design. The preforms extracted from the kayak cannot have overly pronounced curves, as they would be too difficult to reshape. Therefore, the design must prioritize large, flat areas with low curvature. Based on the size of the preform needed to manufacture the paddle, the kayak design has been optimized to maximize the number of preforms that can be extracted. 10 preforms can be extracted from the deck, and 24 from the hull. Preforms were extracted on one half of the kayak to demonstrate that.

### Manufacturing process validation

One of the important factors to consider in the design is the manufacturing method. Here, the infusion process chosen to align with the 3R resin characteristics must not hinder the production of the kayak. A few considerations need to be taken into account. Infusion is an open-mold process, which means only one side is in contact with the mold (side A). This side A will be smooth, while the infusion side, side B, will be rough. Therefore, the B-side of each kayak component must be reserved for a non-functional surface. In this case, the B-sides are the ones enclosed inside the kayak, while the A-sides are reserved for all the visible surfaces of the kayak. Another important point concerns the demolding of the part. In fact, only surfaces with an angle greater than 2 degrees can be demolded. This is why a minimum angle is given to the vertical walls of the deck seat. The flange has a negative angle relative to the demolding axis, which cannot be achieved with a single mold. The manufacturing of the flange was made possible by adding a partition to the mold, which can be removed before demolding as shown in Figure 45. Parts after infusion were visually controlled and no defects were detected, showing that the infusion process with 3R resin was successful on the kayak.



Figure 44. Cutout from the kayak for the paddle reshaping

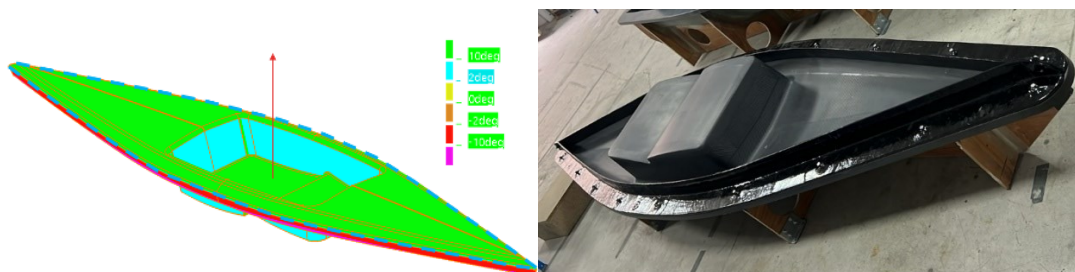


Figure 45. Draft angles for demoulding (left) and Deck mold with the flange partition (right)

### Aesthetic finishing

The kayak is a sports product directly intended for the user, so it must be visually appealing. The colors, paints, gloss, logos, and stickers—everything is carefully designed to give the kayak an aesthetic dimension, which is a key factor in the consumer's decision-making process. Moreover, it is important to prove that using recyclable materials does not mean any compromise in terms of aesthetic finishing for the user.

This final step involves applying the first layer of paint. Then, the stickers of the MC4 and Managing Composites logos, as well as the red stripes, are applied. Finally, the kayak is coated with lacquer, which provides protection and shine to the paint.



Figure 46. Final visual of the kayak

### 7.2.2 Paddle

#### Mechanical performance validation

The kayak paddle is a component subject to significant mechanical stresses. Indeed, analyses have shown that a rower can exert a force on the paddle of up to 200N. This force was the starting point for dimensioning the paddle.



Figure 47. Load case of paddle

The properties of the thermoformed vitrimer material were characterized by CIDETEC. For the reliability of the study, it was important to consider the actual mechanical properties of the recycled material. To achieve this, mechanical tests were conducted on specimens that underwent thermoforming after an infusion, as is the case for the paddle. Additionally, studies demonstrated that the material did not experience any significant loss of strength or stiffness after thermoforming.

The initial studies quickly demonstrated that the laminating sequence considered for the kayak could not withstand the mechanical stresses of the paddle. The numerical simulation showed a displacement of 434mm which would have led to rupture of the material. The solution was therefore directed towards a paddle that incorporates twice the laminate of the kayak, where two preforms would be assembled using a vitrimer adhesive to form the paddle. In addition, a glass fibre insert is added to reinforce the area of the paddle that is most subjected to stress.

Table 11. Paddle elements

Number	Part	Material
1	Adhesive	DP 490 – 0.3mm
2	Oar	Carbon fibre
3	Paddle	G-Weave 360P MC4-F21
4	Paddle reinforcement	Glass fibre G-10

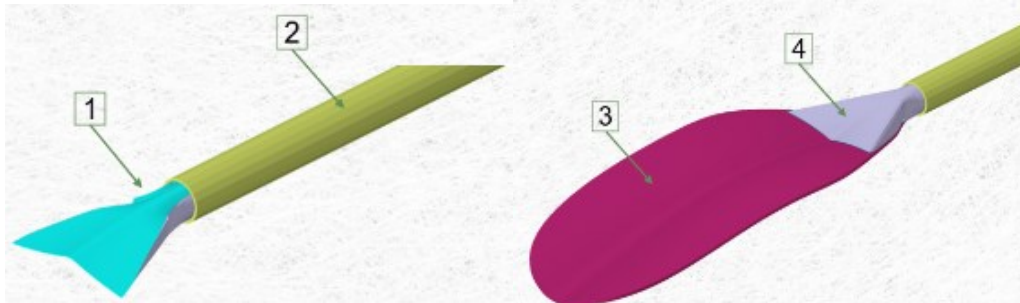


Figure 48. Adhesive and oar (left), paddle and its reinforcement (right)

The finite element analysis iterations validated this new paddle configuration, demonstrating its mechanical strength in use.

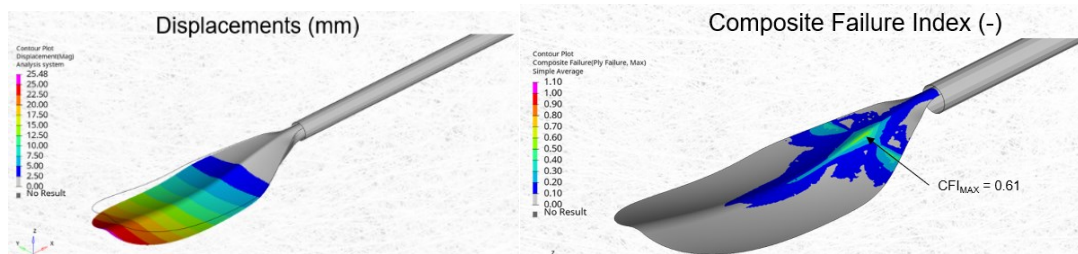


Figure 49. Displacement (left) and failure (right) numerical validation

To validate physically mechanical properties of the paddle, studies are conducted directly on the geometry of the thermoformed paddle derived from the infusion of the entire kayak. These studies aim to validate the mechanical properties at the demonstrator scale. The mechanical tests are conducted on a flattened preform extracted from the kayak and a flattened preform extracted from the paddle to determine the recovery ratio after reshaping. Results are shown in Figure 50.

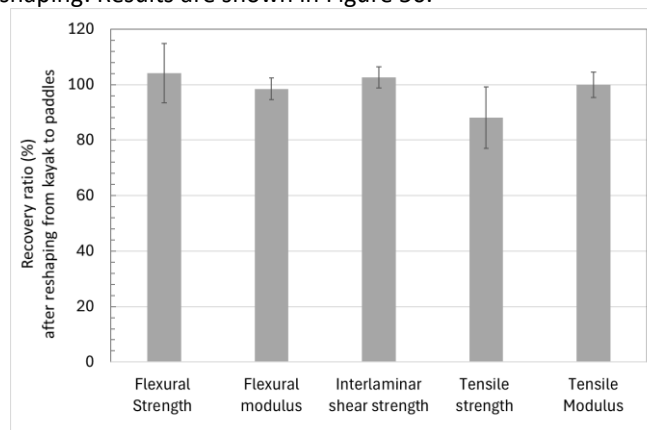


Figure 50. Properties retention ratio of 3R GFRP, from the primary material (3R Kayak) to the recycled part (3R thermoformed paddle)

These ratios are very good in what regards flexural and interlaminar shear properties, with a full retention of the properties. As for the tensile properties, the retention ratio is also good (over 85%), but slightly lower.

**DSC and TGA**

T<sub>g</sub> values of samples extracted from the kayak and the paddles are found to be the same, within the measurement uncertainty (75.5°C and 75.1°C). In the same way, both demonstrators exhibit the same degradation profile, as measured by TGA. The temperature at 5% weight loss is found to be 292.2°C for the kayak demo, and 291.8°C for the paddle. These results confirm the insignificant effect of the repurposing process on 3R GFRP material. Besides the glass fibre weight fraction was measured to be 66.8 wt.% for the kayak and 68.7 wt.% for the paddle, which further indicates that 3R GFRP is barely affected by the reshaping process.

#### Optical microscopy – lay-up integrity

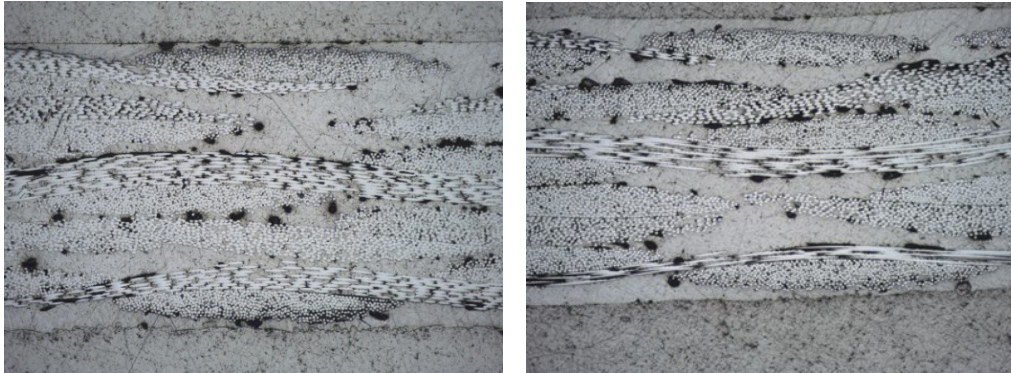


Figure 51 Micrographs of kayak section (left) and paddle section (right)

Composite samples extracted from the paddle, as well as from the initial part (3R kayak), were examined using optical microscopy. Both the primary composite samples (kayak part) and the thermoformed reprocessed composite sample displayed similar microstructures, revealing a highly uniform organization of the glass fibre fabric layers in the observed sample sections. The only defects observed were some voids, which originated from the initial infusion process. This suggests that the thermoforming process does not significantly disrupt the lay-up when reshaping the reference material (kayak part) into the paddle section.

#### Optical microscopy – Adhesive layer consistency

Optical microscopy was also employed to assess the consistency of the adhesive layer used to bond the 1.5 mm thick plates, which were combined to achieve the 3 mm thickness required for the paddle blade. As observed, the adhesive layer is not readily distinguishable within the resin layer, as it would be in cases of non-continuous bonding or the presence of elongated voids. Instead, the adhesive layer is identifiable by the presence of small darker points, observable only upon close inspection near the centre of the section. These darker points correspond to the cross-section of the fibres contained in the 3R adhesive supporting. Additionally, the resin layer containing the adhesive line does not appear significantly thicker than other resin layers within the lay-up. This observation confirms that the adhesive film thickness was sufficient to ensure the proper application of adhesive between the two composite plates.

#### Ultrasonic NDT

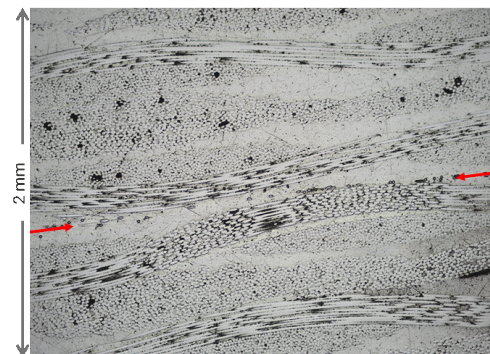


Figure 52. Representative image of the thermoformed paddle. The red arrows indicate the position of the adhesive layer.

To conduct the phased array ultrasonic inspection, a slice of the paddle was extracted from the most critical zone of the paddle, i.e. its central zone, where wrinkles were apparent after thermoforming. The results are presented in the figure below. The 2D mapping of normalized return signal amplitude indicates that the sample presents defects in the full length of the section, with a more pronounced attenuation in the curved area, as shown by the very diffused output sound echo perceivable in this zone. This indication is coherent with the presence of superficial wrinkles.

Overall, this paddle sample appears to be in a state that is not as good as observed after the first thermoforming trials at industrial scale. This may be explained by different observations made on the studied material. The first straightforward observation is the presence of wrinkles in these final samples, that were not present during the first trials. The formation of these wrinkles may be due to the need for double bending of the material sheet in this paddle version, but also to some characteristics of the initial material (3R kayak). Indeed, it was found that the resin content in the 3R kayak (primary material) is around 10% lower, thus lowering the thermoconformability of the material. Besides the optical microscopic evaluation of the material showed a quite higher voids content in the 3R kayak (primary material) – and subsequently in the thermoformed paddle – in comparison with the 3R composite plate and thermoformed paddle extruded section previously studied. Through a detailed image analysis using ImageJ software, while the voids content was evaluated to be  $3.0 \pm 0.7\%$  in the material used for the first trials, it was determined to be  $4.9 \pm 0.4\%$  in the 3R kayak material, indicating that the primary material was not so compacted. This significantly higher voids content in the primary material, which is then found in the thermoformed material, renders the interpretation of the phased array ultrasonic inspection challenging.

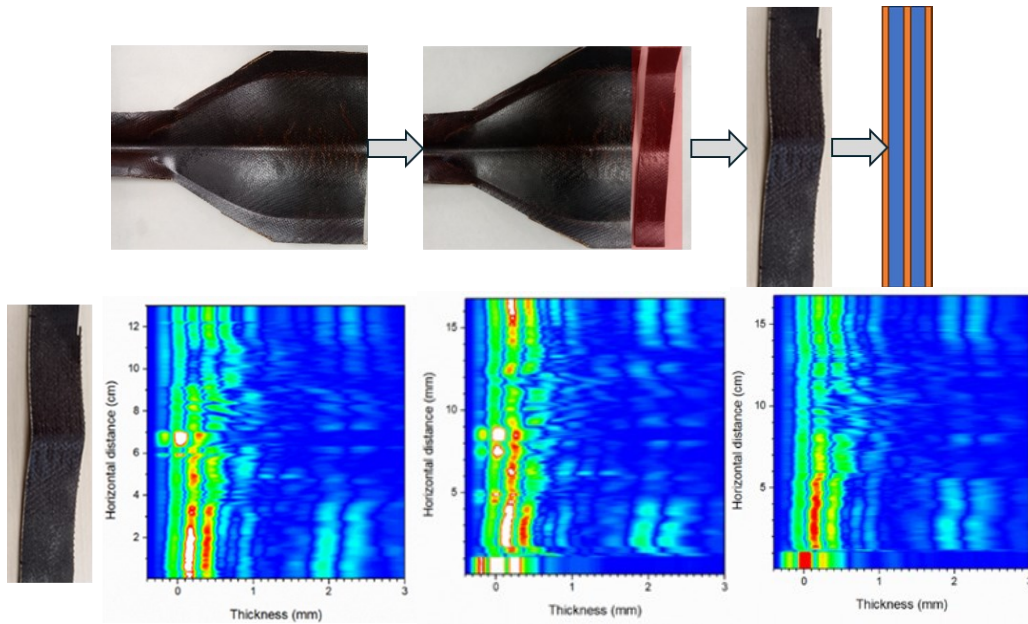


Figure 53. Upper panel: pictures of the paddle, trimmed paddle section, scheme of the scanned

### Manufacturing process validation

Recycling parts made from 3R resin does not offer much flexibility in terms of process choices. Indeed, thermo-compression is the only method that allows for reshaping and thus giving the product a new life. Additionally, this process does have some limitations regarding the geometry of the product to be reformed. The reshaping of the part takes place in a metal mold mounted under a press, where the material is gently brought into its final shape through the action of pressure.



Figure 54. View of the paddle preform and its mould

The paddle cannot accommodate overly sharp curves or details that would be impossible to form. This limitation mainly affected the connection between the frame and the tube. In fact, a widely used solution is to create a hollow section at the end of the paddle to insert the tube, as shown in the following image.



Figure 55. Conventional fibre paddle

By thermoforming the paddle, this solution may be possible to achieve but would require much more development in the process. During the project, the risk of developing this solution was not taken, as it would have resulted in significant additional costs in case of failure. This is why the paddle ultimately includes a mechanized glass fibre insert, which helps absorb the stresses in this highly stressed area, while maintaining a geometry that is unlikely to cause issues during thermoforming. The final thermoforming of the paddle from the preforms of the kayak showed that the process was a success with this paddle geometry.



Figure 56. Thermoformed paddle with GF insert

### Aesthetic finishing

For the same reasons as with the kayak, the finish is an important aspect of the development of the paddle. It is crucial to demonstrate that a part made from recycled materials can have the same visual appearance as one made from virgin materials, and that the user should not have to compromise on the aesthetics of the product when choosing the recycled version.



Figure 57. Finalized paddle

### 7.3 *Virgin materials product comparison*

---

The use of recyclable materials in the case of kayaks or recycled materials in the case of paddles leads to modifications that need to be considered during the product development phase. Indeed, a product may have undergone many years of development and improvements with a given material, and a change in material inevitably requires some adaptations. In this section, the main considerations are presented to take it into account when using 3R resin in kayak manufacturing and recycled preforms in paddle manufacturing.

Vitrimer resins represent a relatively recent advancement in composite materials, first introduced in the early 2010s. Vitrimerers are a class of thermosetting resins that, unlike traditional thermosets, can be reprocessed and reshaped after curing due to their dynamic covalent bonds.

#### 7.3.1 **Kayak**

---

Regarding the development of the kayak, the 3R vitrimer resin replaces a conventional epoxy resin. In this section, we explain the considerations that were taken into account in the kayak development, in terms of design, mechanical performance, and fabrication process.

##### Design considerations

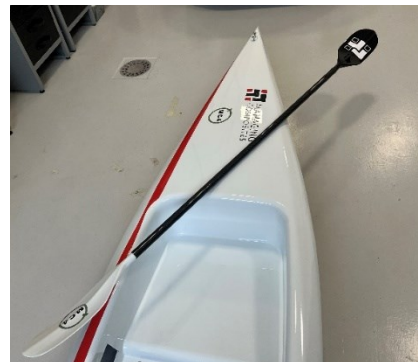
The use of vitrimer resin as a replacement for conventional epoxy resin does not inherently affect the design of a component. Indeed, the infusion process remains the same, and therefore no design modifications related to the process are required. However, as explained earlier, the use of vitrimer resin is driven by the desire to reuse materials at the end of their life in order to reshape them into another product. It is therefore essential that preforms can be extracted from the part made with vitrimer resin. CIDETEC has clearly demonstrated that preforms with pronounced curvatures can cause material breakage during the flattening of the preforms, as shown in Figure 58.



*Figure 58. Flattening defect with sharp curvature*

However, it was observed that adding fibres at  $\pm 45^\circ$  in the composite positively affected the reshaping process, eliminating the breakage problems during the flattening with pronounced curvature. Nevertheless, to minimize the risk of mechanical losses in recycled parts, it remains preferable to prioritize flat and gently curved areas for the reuse and reprocessing of parts made with vitrimer resin.

In the kayak development, this was particularly taken into account, making surfaces flatter and allowing large surface without strong curvatures. However, everything was made so that the resulting design does not affect kayak performance or aesthetics.



*Figure 59. Finalized kayak*

**Mechanical performance of 3R resin**

During the design phase, the mechanical properties of the materials play a very important role. The definition of the laminate, with its orientations and thickness, is directly linked to the mechanical performance. Switching from one material to another always introduces uncertainties in the development of a product. In this case, it is legitimate to ask whether there are notable differences between a product made from glass fibre with a conventional epoxy resin or a 3R vitrimer resin.

This comparison was made through a structural analysis of the kayak. Initially, the kayak was simulated by considering the properties of the Chomarat G-Weave 360P glass fibre fabric with conventional epoxy resin. Then, after characterizing the material used in the construction of the kayak with Chomarat glass fibre fabric and the 3R resin from CIDETEC, the numerical model was updated with these data obtained from mechanical tests. Properties can be compared in Table 12.

Table 12. Mechanical properties comparison between Chomarat glass fibre composite with conventional epoxy and with 3R resin

PROPERTIES	UNIT	Conventional epoxy with G-Weave 360P	3R epoxy with G-Weave 360P
Density	kg/m <sup>3</sup>	1970	1970
Layer Thickness	mm	0.32	0.32
E11 [Young Modulus 0°]	GPa	37.47	21.60
E22 [Young Modulus 90°]	GPa	37.47	20.80
v12 [Poisson Ratio]	-	0.05	0.05
G12 [Shear Modulus]	GPa	12.10	3.25
σ11 [Tensile Strength 0°]	MPa	450	436
σ22 [Tensile Strength 90°]	MPa	450	369
σ11 [Compression Strength 0°]	MPa	450	238
σ22 [Compression Strength 90°]	MPa	450	248
τ12 [IPSS]	MPa	70	48.26
T12 [ILSS]	MPa	50	40.4

The simulations are compared in the images below.

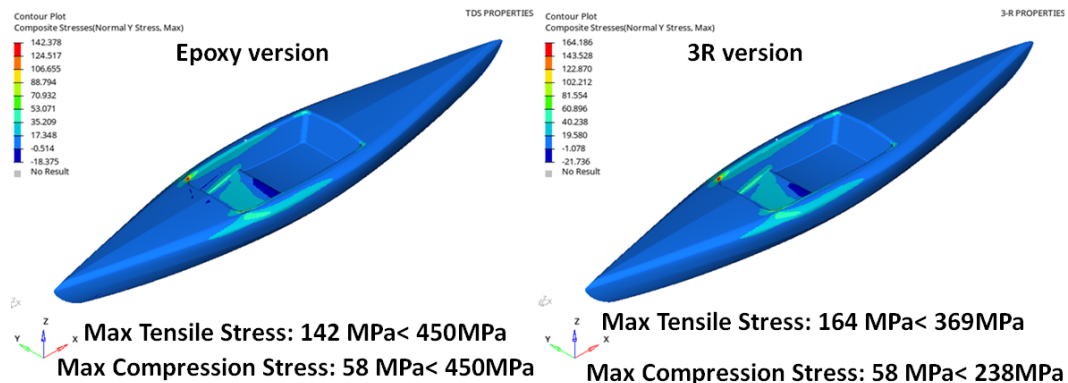


Figure 60. Tensile and compression max strength comparison

Table 13. Kayak performance comparison

Performance under same loads	Max deformation (mm)	Composite failure index (failure >1.0)	Weight (kg)
Virgin	21	0.32	Equal
Re-shaped	33	0.42	Equal

The simulation allowed us to verify that the model with 3R meets the mechanical criteria, with maximum stresses lower than the allowable stresses and maximum displacements that are not critical. The same laminate is therefore validated with both versions, meaning that the use of 3R resin in the kayak does not result in an increase in thickness and thus weight compared to the epoxy version.

However, the kayak version with 3R resin does have a greater maximum deformation than the epoxy version. In addition, the margin between the maximum stress and the allowable stress is smaller in the 3R version than in the epoxy version. This results in a slightly lower safety factor in the 3R version compared to the epoxy version. Reducing this safety factor in the epoxy version is not a feasible solution to save weight because the displacement and, therefore, the rigidity of the kayak would have been a critical point and would not have allowed proper use of the product.

### **Manufacturing process with 3R resin**

The principle of infusion with conventional epoxy resin and 3R resin is very similar. However, there are some differences in the preparation of the resin. A conventional epoxy resin for infusion generally consists of part A and part B that are mixed in order to initiate the polymerization reaction. In the case of 3R resin, part B (hardener) is in a solid state at room temperature. Therefore, it is essential to heat it to 80°C to liquefy it and mix it with the resin itself, which is heated to 60°C.

This heating and melting step of the hardener adds an additional stage to the entire resin preparation process, but its execution is not complicated, which would not hinder its implementation in production.

Another important point when comparing conventional epoxy and 3R resin is that the infusion process is generally carried out at room temperature, especially for large part manufacturing. Infusion is a process that does not require significant investments in machinery, even for large part manufacturing. On the other hand, the vitrimer 3R resin requires a mandatory infusion temperature of 60°C to be sufficiently fluid, along with a curing temperature of around 130°C. For small or medium-sized parts, reaching these temperatures in production is not a major issue. However, it becomes more challenging to heat a boat hull or wind turbine blades, which can be several tens of meters long, to 130°C. This adds a complexity during production, but once again, the solution does not seem impossible.



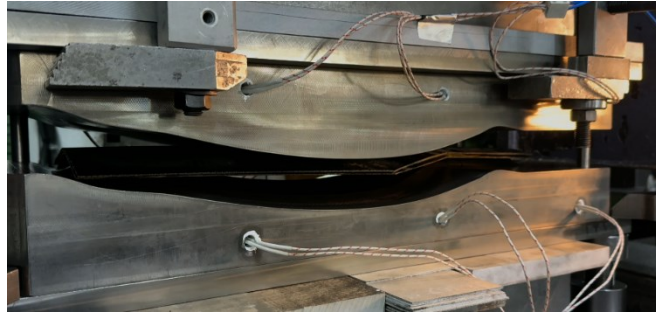
Figure 62. Hardener heating

### 7.3.2 Paddle

---

#### Thermoforming process

The thermoforming process of the kayak hull is directly linked to the 3R resin. The use of existing preforms to reshape them necessarily involves the application of pressure and heat. The preferred process for manufacturing from recycled vitrimer materials is then press thermoforming in a metal mold. This process closely resembles the stamping of thermoplastic composite materials. Indeed, vitrimer resins are often described as having thermoplastic behavior once polymerized. This process is therefore a well-known method that has benefited from many years of development, and it is not specific to the recycling of vitrimer materials. It is widely used today in industry. The advantage of this process is its relative simplicity in implementation with basic equipment such as an oven and press, and the high production rates it can achieve (around 20-25 pieces per hour).



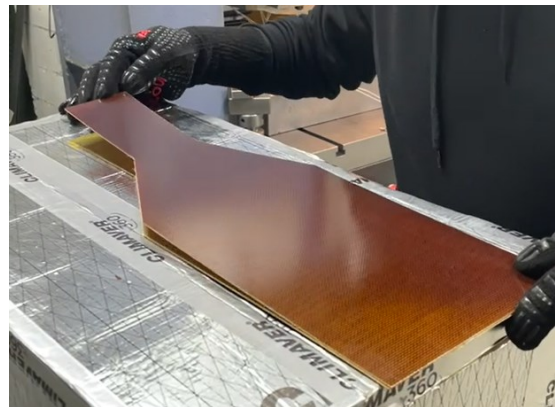
*Figure 63. Thermoforming of the paddle*

The main limitation of this process concerns the geometry of the part to be reshaped, which cannot have too small curvature radii or abrupt changes in geometry, as the laminate would not adapt well in these areas.

In the case of the paddle, a conventional epoxy resin would have allowed for the selection of a different process, such as infusion or prepreg molding, to enable a geometry with more complex shapes. As mentioned earlier, the thermoforming process was unable to create the joint area between the tube and the blade as seen in conventional composite paddles. Once again, it is worth noting that this was a risk not taken during the project. Thermoforming complex-shaped parts require more advanced development with numerous tests to be conducted, but in the case of the paddle, it does not seem impossible. Therefore, it is highly probable that with further development of the product, it will be possible to create a recycled paddle with 3R resin that features a joint with the tube similar to paddles on the market made with virgin materials.

#### No choice of laminated

Another very important point concerning the manufacturing of parts from recycled vitrimer preforms is the choice of the laminate. Indeed, the thermoformed part is directly derived from an already existing laminate that was not specifically developed for it. The paddle is a part that is mechanically highly stressed and must withstand greater forces than the kayak itself. Therefore, the same laminate used for the kayak is not suitable for being reshaped into a paddle, as we showed earlier. To address this problem, the paddle incorporates the kayak laminate twice, which was made possible by bonding two preforms from the kayak with a vitrimer adhesive. However, it is



*Figure 64. Assembly of 2 preforms from the kayak*

possible that this is not the ideal laminate, and developing the paddle without this constraint would have led to a more optimized laminate with virgin materials.

**Mechanical performance of thermoformed materials**

From a technical level point of view, the characteristics of the 3R laminate are different than the virgin 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.

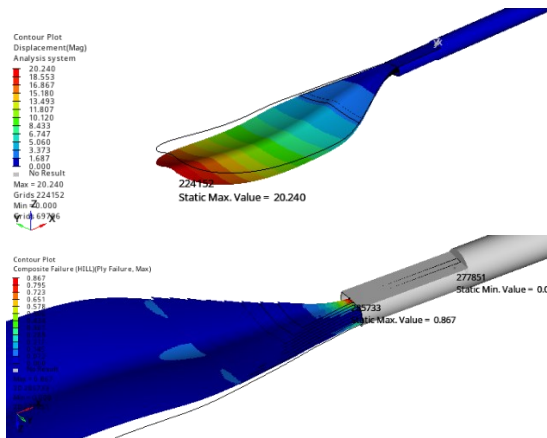


Figure 65: Max. deformations and stresses for virgin material

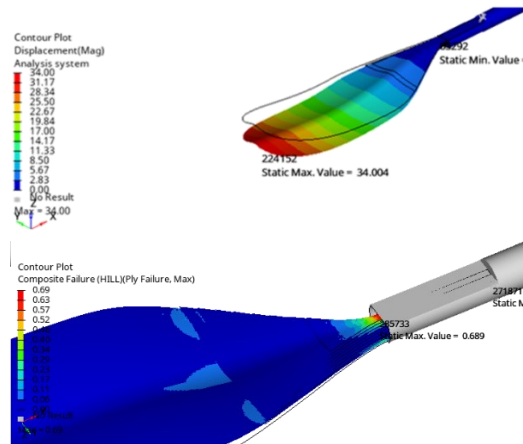


Figure 66: Max. deformations and stresses for 3R material

Table 14. Paddle performance comparison

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

**7.4 Economical evaluation**

Table 15. Economic review of the developed products

Kayak		
	Virgin glass fibre material with commercial resin	Virgin glass fibre material with recyclable 3R resin
Material (glass fibre + resin) extra cost	€ 0	€ 1781
Moulding heating amortization	€ 0	€ 27
Amount of material used	Same	Same
Extra cost per unit	€ 0	€ 1.808
Regular sales price	€ 1.800	€ 3.608

% price increase		100%
<b>Paddle</b>		
	Virgin glass fibre material with commercial resin	Re-shaped from second life glass fibre with 3R resin
<b>Nonrecurring process related costs</b>		
-Mold amortization	€ 8	€ 0
-Autoclave/RTM amortization	€ 8	€ 0
-Laminate cutting system	€ 3	€ 0
-Thermoforming tool amortization	€ 0	€ 8
-Small press	€ 0	€ 7
<b>Recurring related costs</b>		
Material cost	€ 8	€ 0
Amount of material used	Same	Same
-Lamination, curing and trimming	€ 75	€ 0
-Thermoforming process (heating + men-hour)	€ 0	€ 25
Total cost (2 units, left/right)	€ 102	€ 40
Savings per 2 units (left/right)		€ 62
Number of full paddles extracted form 1 kayak		8
Business case is even if this number of paddles are built from recyclable material:		29

While the saving cost per paddle made with 3R recycled material is 62€, it would be necessary to fabricate 29 paddles from one single kayak to compensate for the extra fabrication cost of the kayak with the 3R resin. In this case, only 8 full paddles can be extracted from the kayak.

### ***7.5 Design and manufacturing lessons learnt***

It was explained earlier the challenges faced in the development of the demonstrators with the vitrimer resin, both from a design and manufacturing perspective, and how these issues were resolved. More broadly, with the experience gained during this development, the limitations identified in the use of 3R resin for reshaping are as follows:

- The developed product must be large enough to extract preforms of a suitable size to allow the reformation of other recycled products. That shows that the use of vitrimer resin is not ideal for small parts of less than about 20\*20 cm, which would be the minimum suitable size for considering thermoforming. The larger the developed part, the more opportunities there will be to give it a second life through reshaping.
- The product must have flat areas with low curvature or prioritize reinforcements at  $\pm 45^\circ$  relative to the axis of curvature. Nevertheless, integrating fibres at  $\pm 45^\circ$  to facilitate thermoforming is not always seen as a hindrance to the development of the composite. Indeed, most composite parts incorporate this type of laminate to achieve quasi-isotropic properties. Parts made with unidirectional fibres then have no real benefit in being developed with a vitrimer resin, but this remains a minority in the world of composite materials.

- Resin infusion with 3R resin adds extra step of hardener heating and curing at 130°C which make the process more complex especially for large parts.
- 3R resin is more expensive than conventional epoxy due to the higher price of hardener.
- The thermoformed parts have geometry limitations or need careful development to obtain complex geometries.
- Thermoformed parts are more likely subject to wrinkles and small defects compared with other virgin material processes.
- The recycled part made from existing preform cannot benefit from proper mechanical development to suit perfectly its need as it must adapt to an existing laminate. However, it was demonstrated during the project that it was possible to joint several laminates together to increase mechanical properties, showing that there is still some place for adjustments.

The following advantages of using 3R resin for reshaping have been identified:

- From a global perspective, the use of 3R recycled preforms allows for a reduction in manufacturing costs of the reshaped part, 60% reduction in the case of the paddles.
- When compared with other recycling methods, the reshaping offers a very affordable process where no mechanical properties loss is observed from the initial part.
- The thermoforming is a process that does not require extended experience of working with composite material compared with other processes that require highly qualified operator due to the difficulty of lamination.
- From a life cycle point of view, the reshaping of the paddle offers a very reduced environmental impact when compared with virgin materials.

The kayak development with the paddle reshaping highlighted some technical differences when working with vitrimer resin compared to conventional epoxy. The benefits observed have a significant impact, with a 60% reduction in production costs of the reshaped part and a greatly improved environmental impact. The conclusion of this study is that the technical challenges are of relatively low importance and are largely manageable for a large number of sports equipment parts, considering the benefits that reshaping brings.

## 8. URBAN FURNITURE MADE FROM RECYCLED MATERIALS

### 8.1 *Recycling and manufacturing process description*

---

LAB23's "Soul Bench" demonstrates a commitment to circular economy principles by utilising recycled Glass Fibre Reinforced Concrete (GFRC) in its production. This process minimises waste and reduces reliance on virgin materials.

#### **Recycling Process**

The recycling process begins with the collection of end-of-life GFRC automotive parts, primarily from buses supplied by VDL, LAB23's partner. Future expansion will involve collaboration with local recycling centres, manufacturers, and demolition companies. The collected GFRC waste is then processed using an industrial granulator, shredding it into smaller flakes or strands. This shredded material is then cleaned via air blasting to remove any contaminants or loose fibres, although this step is optional depending on the condition of the waste.

#### **Manufacturing Process**

The manufacturing process involves hand lay-up and casting. First, a mould, fabricated from glass fibre, is prepared and coated with a release agent. For hand lay-up, a gelcoat resin layer is applied, followed by 25kg of virgin glass fibre. The shredded, recycled GFRC is then mixed with unsaturated polyester resin (55kg per bench) and fillers like recycled glass powder. 100kg of this mixture is then applied to the mould in layers, ensuring even distribution and consolidation, until the desired thickness is reached. Alternatively, for the casting process, the mixture is simply poured into the mould. The composite is then cured under controlled temperature and humidity. After curing, the bench is carefully removed from the mould and undergoes finishing operations like trimming and polishing. Finally, the bench is ready for installation, with optional features like armrests, chargers, or speakers added based on customer needs.

#### **End-of-Life and Circularity**

At the end of the bench's life, the GFRC material is collected, and any additional components are separated for reuse or recycling. The GFRC itself is then reprocessed by shredding and can be reused in new composite products. This may involve mixing with virgin resin, glass fibre, and gelcoat, or using it in less demanding applications. Throughout the process, material tracking is maintained to monitor the circular flow, and collaboration between stakeholders is emphasized to ensure the process's overall success.

#### **Material Flow Chart**

[End-of-Life GFRC Automotive Parts (VDL)] --> [Collection] --> [Shredding/Grinding (Granulator)] --> [Cleaning (Optional)] --> [Resin Preparation (Unsaturated Polyester Resin + Fillers)] --> [Mixing (Shredded GFRC + Resin)] --> [Mould Preparation (Glass Fibre Mould + Release Agent)] --> [Hand Lay-Up (Virgin Glass Fibre + GFRC Mixture) OR Casting (GFRC Mixture)] --> [Curing] --> [Demoulding] --> [Finishing] --> [Urban Bench (Soul Bench)] --> [Installation & Use] --> [End-of-Life] --> [Component Separation] --> [Reprocessing (Shredding)] --> [New Composite Products]

This circular process chain allows LAB23 to create sustainable urban furniture, minimising waste and promoting a circular economy within the manufacturing sector.

## ***8.2 Technical specifications assessment***

---

The Soul Bench has undergone initial testing to assess its suitability for outdoor urban environments carried out by the IUAV University of Venice, in order to evaluate the performance and quality of the product.

### **Structural strength**

The bench is subjected to load tests to verify its strength and stability. Preliminary results have shown that the shredded glass fibre, combined with binders, provides high load capacity and excellent impact resistance.

### **Visual Inspection**

The bench's surface finish and overall aesthetic were evaluated, confirming it meets the design specifications. The recycled GFRC exhibits a unique texture that differentiates it from products made with virgin materials.

### **Load Testing**

Static load testing was performed to simulate real-world use, including seating and weight distribution. The bench demonstrated sufficient structural integrity and stability under the applied loads.

### **Durability Assessment**

The bench has been exposed to typical outdoor conditions for a limited period. No significant signs of degradation have been observed.

### **Material Analysis**

Samples of the recycled GFRC have been analysed to determine its composition and mechanical properties.

By implementing this circular process, LAB23 creates sustainable urban furniture from recycled GFRC, minimising waste and contributing to a circular economy. The Soul Bench represents a tangible demonstration of our commitment to sustainable design and manufacturing.

## ***8.3 Virgin materials product comparison***

---

Table 16. Comparison table between the MC4 Soul bench and a standard production bench

<b><i>MC4 PRODUCT FEATURES Soul bench</i></b>	<b><i>Quantity in units KG</i></b>	<b><i>STANDARD PRODUCT FEATURES Soul bench</i></b>	<b><i>Quantity in units KG</i></b>
<b><i>GFRC</i></b>	<b><i>100 kg</i></b>	<b><i>Construction Stone Grit</i></b>	<b><i>84 kg</i></b>
<b><i>Virgin glass fibre</i></b>	<b><i>25 kg</i></b>	<b><i>Virgin glass fibre</i></b>	<b><i>25 kg</i></b>
<b><i>Unsaturated polyester resin</i></b>	<b><i>55 kg</i></b>	<b><i>Unsaturated polyester resin</i></b>	<b><i>71 kg</i></b>
<b><i>Gelcoat</i></b>	<b><i>25 kg</i></b>	<b><i>Gelcoat</i></b>	<b><i>25 kg</i></b>

The circular process chain for hand lay-up and casting of a shredded GFRC urban bench based on the use of recycled GFRC involves the following differences between recycled GFRC and Virgin Materials, Challenges, and Solutions:

Using recycled GFRC presents unique challenges compared to virgin materials like virgin glass fibre and construction stone grid. These challenges arise from variations in the recycled material stream and the potential degradation of the GFRC during its first life cycle and the recycling process.

#### **Material Variability**

Recycled GFRC is likely to have varying fibre content, resin type, and filler composition depending on its original application. This inconsistency can affect the final product's mechanical properties. Solution: Rigorous quality control measures are essential. This includes:

- Incoming material inspection: Analysing samples of the shredded GFRC to determine fibre content, resin type, and any contaminants.
- Blending and homogenization: Thoroughly mixing the shredded GFRC to create a more homogenous material before it's incorporated into the new composite.

#### **Fibre Degradation**

The glass fibres in recycled GFRC might be damaged or shortened during the shredding process, leading to reduced strength compared to virgin glass fibre. Solution:

- Optimised shredding: Carefully controlling the shredding process (e.g., using granulators with specific blade designs and speeds) can minimise fibre damage.
- Strategic use of virgin fibre: The "Soul Bench" design incorporates 25kg of virgin glass fibre in the hand lay-up process. This strategic addition of virgin fibre compensates for potential strength reductions in the recycled GFRC component, ensuring structural integrity, particularly near the surface. The virgin material is placed where the structural requirements are highest, while the recycled material is used mainly for the core.
- Design considerations: The structural design of the bench should account for the potentially slightly lower mechanical properties of the recycled GFRC compared to virgin material. Thicker sections or reinforcing features might be necessary.

#### **Contaminants**

Recycled GFRC might contain contaminants (e.g., dirt, paint, metal) that could affect the composite's properties or aesthetics. Solution:

- Cleaning process: The optional cleaning stage using air blasting can remove loose contaminants.
- Careful sorting: Before shredding, the waste GFRC should be inspected and sorted to remove any large or potentially harmful contaminants.

#### **Process Adjustments**

The processing of recycled GFRC might require adjustments compared to virgin materials. For instance, the mixing process might need to be adapted to achieve a uniform distribution of the shorter fibres in the recycled material. Solution:

- Process optimisation: Trials and testing should be conducted to optimise the mixing and casting processes for the recycled GFRC blend.

#### **Aesthetics**

The use of recycled GFRC could lead to variations in the final product's colour and surface appearance compared to using only virgin materials. Solution:

- Surface finishing: The finishing process (e.g., gelcoat application, painting) can be used to achieve a consistent and desired aesthetic.
- Embrace the recycled look: The design could also celebrate the recycled nature of the material by incorporating its unique texture or colour variations as a design feature.

Working with recycled GFRC adds complexity to the production process. The level of difficulty depends on the quality of the incoming recycled material and the specific requirements of the final product. However, with careful quality control, process optimisation, and design considerations, it's certainly feasible to create high-quality, durable products like the "Soul Bench" from recycled GFRC. The key is to address the material variability and potential fibre degradation proactively throughout the entire development process. The strategic use of virgin glass fibre is a key part of the solution to address mechanical performance.

## **8.4 Economical evaluation**

The economic viability of LAB23's "Soul Bench" made from recycled GFRC, considering material and process costs, and comparing it to using virgin materials like construction stone grit is based on the LCI data collected and analyzed by IRES through life cycle assessment. The following Table indicates the cost breakdown per cost category for both, MC4 and conventional bench. As observed, cost of raw materials are reduced only by 6% due to the high cost of gelcoat and resin that remains the same in both products. The total LCC of the MC4 soul bench appears to have slightly lower cost than conventional due to the reduction in material cost. However, it's difficult to provide precise figures without specific supplier quotes from the real market and detailed cost breakdowns. Key cost drivers are outlined in sections below and some general comparisons are made.

*Table 17. Cost break-down analysis in all cost categories per FU: 1 piece for the MC4 and the conventional soul bench*

Cost categories	MC4 demo		Conventional demo	
	€ / FU	% of total cost	€ / FU	% of total cost
Cost of Raw Materials	284,00	22,29%	301,60	23,35%
Cost of Operating labor	960,00	75,36%	960,00	74,33%
Cost of Utilities	0,07	0,01%	0,07	0,01%
Cost of Depreciation (FCI)	1,10	0,09%	1,10	0,09%
Cost of Maintenance & Repairs	0,67	0,05%	0,67	0,05%
Cost of Waste Treatment	0,13	0,01%	0,13	0,01%
Cost of Packaging	28,00	2,20%	28,00	2,17%
Cost of Storage	0,00	0,00%	0,00	0,00%
<b>Total cost</b>	<b>1273,96</b>	<b>100%</b>	<b>1291,56</b>	<b>100%</b>

### **8.4.1 Material Costs**

#### **Recycled GFRC**

The primary advantage here lies in the potentially lower cost of the raw material. While there will be costs associated with collection, sorting, and processing the waste GFRC, these are likely to be lower than the cost of virgin GFRC or other comparable materials. The cost of virgin glass fibre (25kg per bench) is a significant material cost.

#### **Resin**

The 55kg of unsaturated polyester resin per bench represents a substantial material cost and will be a similar cost whether using recycled GFRC or virgin aggregate.

#### **Fillers**

Recycled glass powder is a cost-effective filler.

**Virgin Materials** (e.g., Construction Stone Grit)

Construction stone grit is a relatively inexpensive material. However, the cost of transport and processing into a usable form for furniture manufacturing would need to be factored in. The cost of binding agents (cement, etc.) would also be relevant.

**Mould Materials**

The cost of the fibreglass mould is a one-time investment (amortised over the number of benches produced).

---

### 8.4.2 Process Costs

**Waste Collection**

Costs include logistics, transportation, and potentially tipping fees or payments to waste providers.

**Shredding & Processing**

Costs include energy consumption for the granulator, maintenance, dust control measures, and labour.

**Composite Preparation**

Costs include labour for resin preparation and mixing, as well as energy for the mechanical mixer.

**Mould Preparation & Casting**

Costs include labour for mould preparation, gelcoat application, hand lay-up/casting, and curing.

**Demoulding & Finishing**

Costs include labour for demoulding and finishing operations.

**Installation**

Costs include labour and transportation to the installation site.

**End-of-Life Processing**

Costs associated with collecting, separating components, and reprocessing the GFRC for reuse.

---

### 8.4.3 Comparison: Recycled GFRC vs. Virgin Materials (e.g., Construction Stone Grit)

**Material Cost**

Recycled GFRC could offer a significant cost advantage over virgin materials, especially if a reliable and low-cost source of waste GFRC can be secured. However, the 25kg of virgin glass fibre per bench will be a significant cost.

**Processing Cost**

Processing costs for recycled GFRC (shredding, cleaning) are likely to be comparable to or slightly higher than the processing costs for virgin stone grit (crushing, screening).

**Environmental Cost**

Recycled GFRC has a clear environmental advantage, reducing waste and the need for virgin material extraction. This can translate into cost savings related to carbon credits or other environmental incentives.

**Performance**

GFRC, whether recycled or virgin, generally offers better flexural strength and durability compared to traditional concrete made with stone grit. This could translate into longer lifespan and reduced maintenance costs for the "Soul Bench."

---

### 8.4.4 Other Economic Considerations:

**Market Demand**

The market demand for sustainable furniture made from recycled materials will influence the pricing and profitability of the "Soul Bench."

**Branding & Marketing**

Highlighting the recycled content and environmental benefits of the "Soul Bench" can justify a premium price.

**Scalability**

The scalability of the recycled GFRC supply chain will be crucial for long-term economic viability.

### **Life-Cycle Cost Analysis**

A comprehensive life-cycle cost analysis should be conducted to compare the total cost of ownership of the "Soul Bench" (including material, processing, maintenance, and end-of-life costs) with benches made from virgin materials.

#### **8.4.5 Conclusion**

---

The "Soul Bench" has the potential to be economically competitive, especially if the recycled GFRC material stream can be secured at a reasonable cost. A detailed cost analysis, including supplier quotes and process cost estimations, is essential to determine the precise economic viability of the product. The environmental benefits and potential for premium pricing due to its sustainable nature should also be factored into the overall economic assessment. The use of 25kg of virgin glass fibre in each bench is a significant factor in the cost and should be considered for optimisation.

### **8.5 Design and manufacturing lessons learnt**

---

LAB23's with the "Soul bench" product demonstrates the potential of recycled Glass Fibre Reinforced Concrete (GFRC) in creating sustainable urban furniture. Here's an overview of the use of recycled GFRC, considering its strengths, weaknesses, and potential:

#### **Strengths**

- **Environmental Benefits:** The primary strength is the significant reduction in waste and the promotion of a circular economy. By repurposing end-of-life GFRC, the project diverts material from landfills and reduces the demand for virgin resources. This contributes to lower embodied carbon and a more sustainable approach to manufacturing.
- **Material Properties:** GFRC, even when recycled, can retain good structural properties. The addition of virgin glass fibre in the lay-up process further enhances the strength and durability of the final product. The use of fillers like recycled glass powder can also improve certain properties and potentially reduce the overall cost.
- **Design Flexibility:** The hand lay-up and casting process allows for design flexibility. The mould can be shaped to create aesthetically pleasing and functional urban furniture. The integration of additional features (armrests, charging ports, speakers) demonstrates the versatility of the material and process.
- **Potential for Scalability:** While the project currently relies on a partnership with VDL, the plan to engage local recycling centres, manufacturers, and demolition companies suggests a vision for scaling up the process and increasing the volume of recycled GFRC used.
- **Positive Public Image and CAM Minimum Environmental Criteria:** Using a relevant rate of recycled materials aligns with growing public awareness and demand for sustainable products. This can enhance a positive brand image and the compliance with the Minimum Environmental Criteria of urban furniture products subject to CAM obligation for Green Public Procurement at EU level.

#### **Weaknesses**

- **Collection and Logistics:** Establishing efficient collection systems for end-of-life GFRC can be complex and costly. Logistics, sorting, and transportation of waste materials need to be carefully considered.
- **Processing Costs:** Shredding, cleaning, and reprocessing GFRC requires specialized equipment and energy, which can add to the overall cost of the final product. The economic viability of the process depends on balancing these costs with the benefits of using recycled materials.
- **Performance Uncertainty:** The long-term performance and durability of products made from recycled GFRC need to be thoroughly tested and validated. Concerns about potential degradation or changes in material properties over time need to be addressed.

### Potential for the Sector

- **Increased Use of Recycled Materials:** The Soul bench project can serve as a model for other manufacturers looking to incorporate recycled materials into their products. This can drive innovation and create new market opportunities for sustainable urban furniture.
- **Development of Standards and Guidelines:** As the use of recycled GFRC grows, there will be a need for industry standards and guidelines to ensure quality, performance, and safety. This will help to build confidence in the use of recycled materials.
- **Collaboration and Partnerships:** Collaboration between waste management companies, manufacturers, designers, and end-users is essential to create a successful circular economy for GFRC. Partnerships can help to address the challenges of collection, processing, and market development.
- **Expansion to Other Applications:** The technology and processes developed for the Soul bench can be adapted and applied to other sectors, such as construction where GFRC is used.
- **Contribution to Sustainability Goals:** Increased use of recycled GFRC can contribute to broader sustainability goals, such as reducing waste, conserving resources, and lowering carbon emissions.

LAB23's Soul bench product demonstrates the viability and potential of using recycled GFRC in urban furniture. While there are challenges to overcome, the environmental benefits, design flexibility, and potential for scalability make it a promising approach. Continued research, development, and collaboration will be key to unlocking the full potential of recycled GFRC and creating a more sustainable future for the sector.



Figure 67 Soul Bench premiered at the Milan Trade Fair on February 2025

## 9. CIVIL ENGINEERING COMPONENTS MADE FROM RECYCLED MATERIAL

### 9.1 Recycling and manufacturing process description

Different kinds of shredded GFRP materials were analysed from the point of view of their utilization for fabrication of joining collets for civil engineering. Short trials of composite fabrications were conducted in order to find out their processability potential and select proper fabrication method and their parameters. In the case of material obtained from wind turbines blades, additional effort was made to separate composite material from the delivered diverse composition. In total 14 different types of materials fractions were indicated. From that reason and the additional work needed for the separation process, this material after first tests was rejected from further testing.

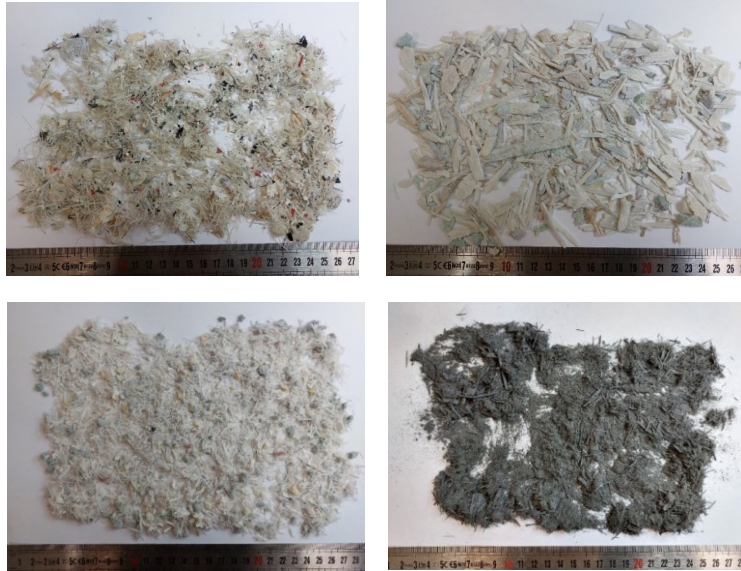


Figure 68. Morphology of shredded materials obtained from different sources.

#### Manufacturing Process of Prototype Joining Collets for Strength Testing and Evaluation of Construction Variants in the Pilot Form

The manufacturing process of prototype joining collets intended for further evaluation of various structural design variants was executed using the compression moulding method. This approach was chosen due to its efficiency in producing high strength composite elements with precise dimensions and consistent material properties. The process of joining collets fabrication based on amine epoxy matrix containing shredded GFRP was divided into few main stages. The first stage of the process involved preparing the composite mixture. This included the careful selection and blending of recycled GFRP with a specially selected NOMA's amine based epoxy resin. The amine based epoxy resins were selected based on their superior processing parameters, including optimal viscosity, curing time, and curing temperature. These characteristics were essential not only for ensuring high quality composite products but also for maintaining the economic feasibility of the manufacturing process. The size and distribution of the shredded GFRPs were carefully controlled to achieve uniform mechanical properties across the final product. The mixture was thoroughly homogenized to ensure consistent resin distribution throughout the composite, which is crucial for achieving the desired strength and durability in the joining collets. Next, the prepared composite mixture containing GFRP recyclate was placed into the cavity of the lower part of an open mould. The mould was then closed by inserting a punch and subjected to pressing. The pressing process was carried out using an adapted single cavity device, allowing for the production of composite rings with varying structures.

After pressing and curing, the bottom plate was removed. Then, by applying force to the protruding pins from the composite joining collet containing grinded GFRP was ejected from the mould along with the punch, which was then easily separated from the final product. Due to the appropriate shape of the pins, they could be easily and safely removed from the finished product. Below in Figure 69 is presented a diagram with the main process steps for fabrication of the joining collets.

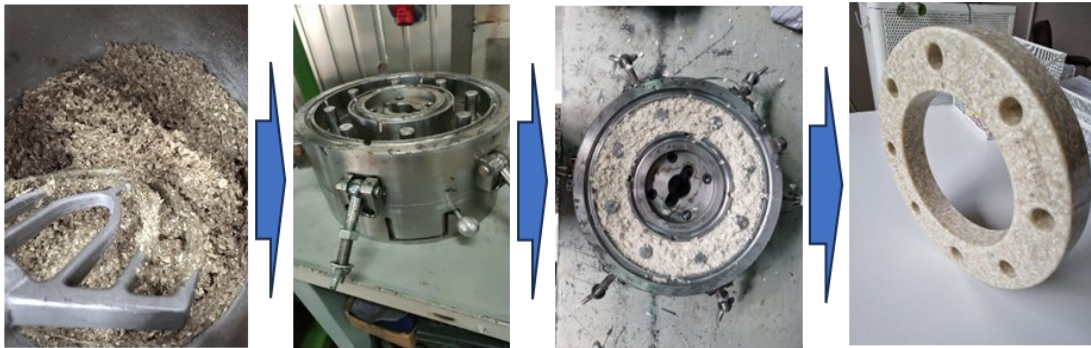


Figure 69. Typical stages of joining collets fabrication.

## 9.2 Technical specifications assessment

At the outset, NOMA developed the concept of the mould, which was also subject to extensive research, continuous modifications, and improvements. The development process involved iterative design evaluations, where initial prototypes were analysed for dimensional accuracy, structural integrity, and compatibility with the composite joining collets. Feedback from preliminary testing led to further refinements, ensuring that the final mould design met both functional and manufacturing requirements.

The characteristic dimensions for the given flange, including the number and diameter of the mounting bolt holes such as the pitch circle diameter of the mounting holes, the diameter of the bolt holes, and their quantity were adopted from the technical standard for flanges: PN-EN 1092-1. This European standard specifies the dimensions, tolerances, and material requirements for circular flanges used in piping systems, ensuring compatibility with existing industrial pipelines and accessories. For other pipe diameters, the mould design followed the same principles, with dimensions taken according to the aforementioned standard. This approach ensured uniformity across different product lines while maintaining adherence to industry standards. The design process also took into account factors such as shrinkage during curing, ease of demoulding, and the structural stability of the mould under high-pressure compression moulding conditions.

To validate the mould design, prototype joining collets were manufactured across the lower, middle, and upper diameter ranges, based on the recommendations of certifying bodies. This included a variety of diameters for different pipe sizes commonly used in industrial applications, ensuring that the joining collets could accommodate diverse pipeline systems. During the testing phase, the mould underwent multiple production cycles to evaluate its durability, dimensional precision, and repeatability. This phase also included the assessment of component surface finish quality, internal stress distribution, and the ability to consistently produce joining collets without defects such as voids or incomplete curing. Adjustments were made to optimize the processing pressure distribution, clamping system, and further enhancing the efficiency and reliability of the production process. The precise dimensions of the joining collets were determined based on the technical parameters of the pipelines and the expected operating conditions. The key parameters considered for joining collets contained GFRP included:

- Pitch Circle Diameter i.e. the distance between the centres of the bolt holes, ensuring compatibility with existing flanged connections.

- Bolt Hole Diameter were determined according to the bolt size specified in the PN-EN 1092-1 standard for each nominal diameter (DN) of the pipe.
- Bolt Quantity: Based on the pipe diameter and pressure class, ensuring secure and even clamping force around the flange.
- Collet Thickness: Calculated based on strength tests, material properties, and the pressure requirements for each pipe size.

The strength parameters of the tested composite samples, along with the requirements of the standard regarding the minimum strength parameters for joining collets, enabled NOMA to determine the appropriate thickness of the joining collets within the required range of accepted diameters. Mechanical tests, including tensile strength, compressive strength, and impact resistance, were conducted on samples taken from demonstrators to ensure that the composite material could withstand the stresses encountered during pipeline operation.

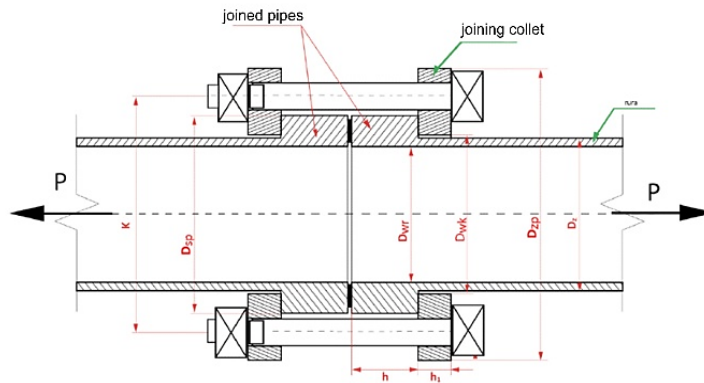


Figure 70. Diagram of the connection and characteristic dimensions necessary for calculating the sizes of joining collets for specified pressures.

The pressure ratings were determined by analysing real world operating conditions, considering factors such as temperature fluctuations, pipeline material properties, and potential mechanical stresses during installation and use.

Further, the work was focused on the technological studies related to the production of joining collets, alongside comprehensive testing of their mechanical and operational i.e. performance properties. The NOMA team conducted in depth investigations into the design of the manufacturing technology for joining collets, specifically for testing purposes. This process was based on the primary technology of compression moulding in

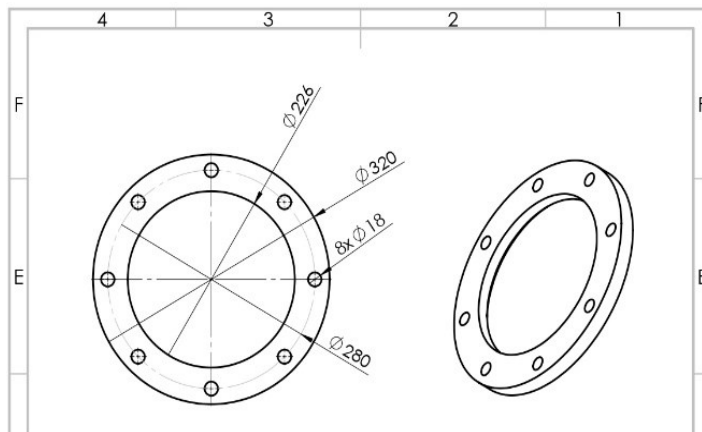


Figure 71. Scheme of joining collet with indicated key dimensions.

telescopic closed moulds i.e. punch die system. The studies also explored the impact of manufacturing parameters on product quality, including the curing systems, process parameters, technological shrinkage, and dimensional accuracy of the rings. A critical aspect of the research involved determining the maximum amount of recycled material that could be added, as well as the optimal form of the recyclate, depending on the specific ring dimensions and working pressures. Based on the results of tests conducted on composite mixtures containing GFRP recyclates, the composition of the mixture was carefully adjusted to

meet the requirements of the compression moulding process. This optimization ensured that the composite material maintained its mechanical integrity, processability, and final product quality while incorporating environmentally friendly, recycled components. After fabrication of joining collets NOMA team conducted extensive testing on individual prototype ring mouldings. These tests were performed using a universal testing machine equipped with specialized tooling designed for evaluating the mechanical properties of the joining collets. The primary focus was on two key areas:

- Bending Strength: The ability of the composite rings to withstand flexural stresses without deformation or failure.
- Crack Resistance: The material's resistance to crack initiation and propagation under load.

The results from these mechanical tests were analysed by NOMA. Based on the conducted tests, iterative improvements were made to both the mould design and the technological process parameters. This adaptive approach allowed for continuous refinement of the production process, ensuring that the final products met the required performance standards. In order to investigate quality of the fabricated components, SEM observations were made to study microstructure of components and check material from the point of view of technological issues like porosity or cracks (Figure 72). The cross-section of the samples revealed by SEM showed an ideal structure, without pores and discontinuities, which confirms that the infusion manufacturing method is suitable for composites with shredded GFRP. In the cross-section can be observed single fibres and fibres agglomerates from “micro composites” contained in the structure of the shredded GFRP filler.

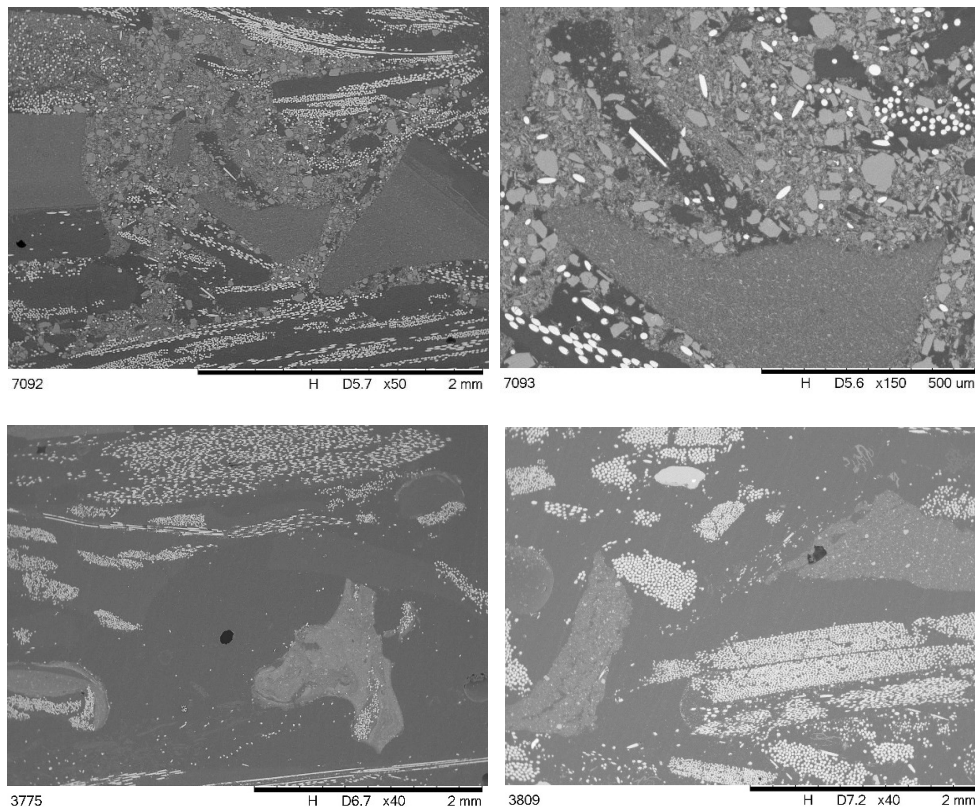


Figure 72. SEM images of typical microstructure of fabricated components.

To further validate the performance of the joining collets, a proof of concept was conducted using a specially constructed test rig designed to simulate real world conditions. This custom built device replicated the operational environment of the joining collets within a flange connection under pressure testing

conditions. During these tests, the joining collets were subjected to controlled internal pressure while installed within a simulated pipeline connection. The aim was to assess their integrity, resistance to deformation, and overall durability under typical working pressures. These trials provided critical insights into how the joining collets would perform in practical applications, ensuring that the design could meet industry standards for safety and reliability.

### 9.3 Virgin materials product comparison

Composite joining collets offer numerous advantages over components made from commonly used materials such as steel, iron, or concrete. These advanced solutions not only provide superior performance but also address many of the limitations associated with traditional materials. Importantly, until now, no composite product based on virgin materials has been available on the market that fulfils the same functionalities as those developed by NOMA in this project. One of the most significant advantages of composite joining collets is their adaptability. They offer seamless customization in terms of functionality, dimensions, colours, and parameters related to strength and resistance, such as resistance to chemically aggressive media. This flexibility allows manufacturers to tailor products to the specific needs of individual customers, ensuring optimal performance in diverse applications.

Another notable benefit is the exceptionally low weight of composite structures. For example, composite elements constitute only approximately 10% of the weight of a comparable reinforced concrete structure, around 20% of the weight of a steel structure, and roughly 25% of the weight of a malleable cast iron structure. This significant reduction in weight minimizes the need for heavy equipment, such as machinery used for laying pipelines or transporting prefabricated elements, thereby substantially reducing investment costs. Furthermore, the lower weight compared to steel pipes and joining collets simplifies storage, loading, and transportation, making these processes much easier, faster, and more cost effective.

In addition to their lightweight nature and customization possibilities, composite joining collets stand out for their high durability and reliability. They exhibit exceptional resistance to corrosion, aging, and environmental degradation, even when exposed to harsh conditions. Extensive tests on the durability of laminates, conducted in leading American and Scandinavian laboratories, have demonstrated that the service life of composite materials exceeds 50 years. After five decades of use, composites retain at least 80% of their initial strength, underscoring their long-term structural integrity and performance. The combination of lightweight construction, high strength, corrosion resistance, and adaptability makes composite joining collets an ideal choice for modern industrial applications. They not only enhance operational efficiency but also contribute to significant cost savings and environmental benefits, positioning them as a superior alternative to conventional materials in pipeline systems and other infrastructure projects.

In this section, different types and contents of shredded GFRPs are compared to neat epoxy resin as the reference material. All shredded materials were incorporated at a content of 50% by weight. Recyclates named "N" and "P" are GFRPs commercially available but coming from two different suppliers.

As indicated in Figure 73, the application of recyclates marked as "N" and "P" did not result in any significant change in flexural strength when compared to the neat NOMA epoxy resin (REF). In contrast, the materials

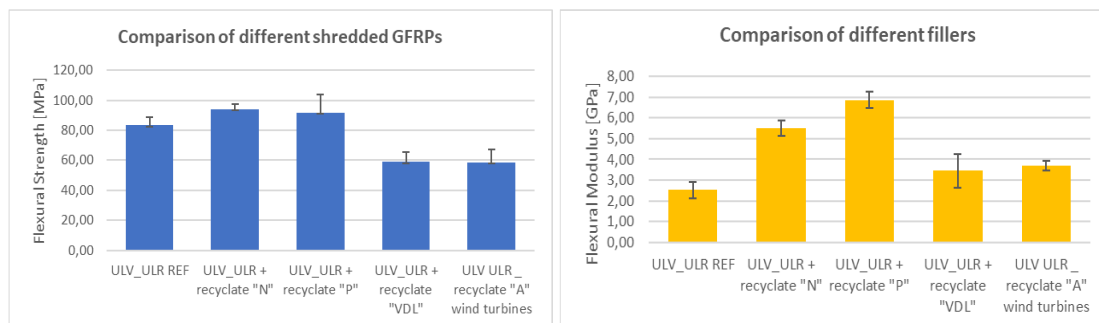


Figure 73. Flexural strength (left) and flexural modulus (right) for composites containing different shredded GFRP materials.

derived from VDL and turbine blades exhibited a noticeable decrease in flexural strength, suggesting that the source and processing history of the recyclate play a crucial role in determining the final performance of the composite material.

In terms of flexural modulus, all tested samples showed an increase in modulus values compared to the neat resin. This increase indicates enhanced stiffness of the composites, which is particularly desirable for structural applications requiring high rigidity. The most significant improvement was observed for samples containing recyclates marked as “N” and “P,” where the flexural modulus increased by more than 150% in comparison to reference sample.

The next step of investigations was the optimization of shredded GFRP concentration in new composites for two shredded materials marked as “N” and “VDL” which gave the highest and lowest modulus changes in comparison to reference neat resin without shredded material. For these purposes, samples contained between 15 and 70 wt.% of shredded materials. In the case of “N” material after application of 70 wt.% of filler, quality of fabricated samples was too low, probably due to too high resin viscosity in the mixture. Below in Figure 74 Figure 75 are presented images of composite plates manufactured with different contents of shredded materials i.e. “VDL”, “N”.

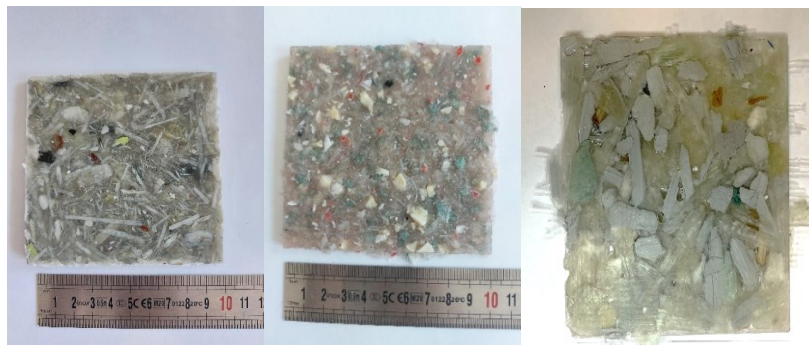


Figure 74. Composite plates with different content of shredded materials

Based on the conducted investigation and comparison to reference neat resin samples and processing parameters it was determined optimal concentration of shredded GFRP material on the level of ~50 wt.% for being the best compromise between both flexural strength and modulus optimization.

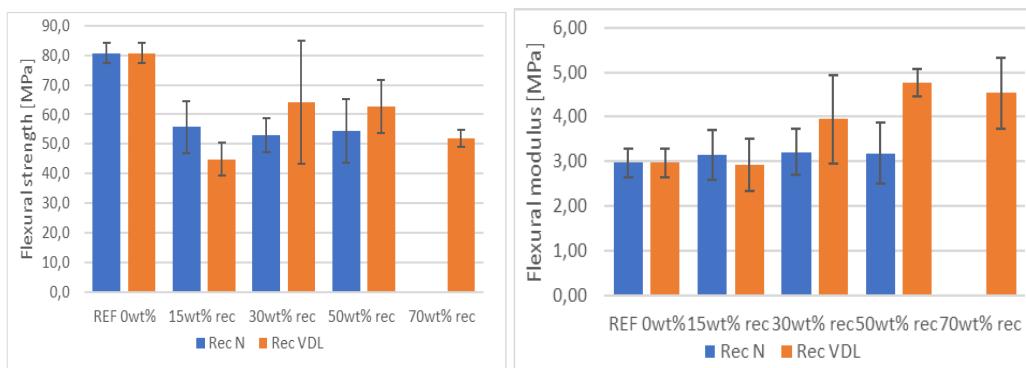


Figure 75. Flexural strength (left) and flexural modulus (right) measurements of composites containing different contents of shredded GFRP materials “N” and “VDL”.

### 9.4 Economical evaluation

To evaluate the economic performance of the recycled composite joining collets, a life cycle cost assessment was conducted based on manufacture data provided for the custom built device (test rig, designed to simulate real world conditions). An annual production of 10,000 pieces and a depreciation time of 10 years have been assumed in the cost assessment to estimate the fixed capital investment. For a joining collet of 10 kg, the LCC, presented in Table 18, is estimated at approx. 545 €/ part with labour being the

main hotspot (64%) and raw materials accounting for 34%. Depending on the market prices of shredded GF material and recycled organic parts from solvolysis (the latter considered as zero cost in the analysis), the total cost of raw materials is expected to vary. The total LCC of a composite joining collet made from virgin materials is expected to be slightly higher (by approx. 5-8%) due to higher cost of shredded virgin GF and virgin resin.

Table 18: Cost break-down analysis of recycled composite joining collet (10 kg) in all cost categories per FU: 1 part

Cost categories	MC4 demo	
	€ / FU	% of total cost
Cost of Raw Materials	183,50	33,69%
Cost of Operating labor	348,00	63,90%
Cost of Utilities	1,64	0,30%
Cost of Depreciation (FCI)	1,02	0,19%
Cost of Maintenance & Repairs	0,44	0,08%
Cost of Waste Treatment	10,00	1,84%
Cost of Packaging	0,00	0,00%
Cost of Storage	0,00	0,00%
<b>Total cost</b>	<b>544,60</b>	<b>100%</b>

## 9.5 Design and manufacturing lessons learnt

The manufacturing process of prototype joining collets using the compression moulding method demonstrated the feasibility of producing high performance composite components with recycled GFRP content. The careful selection of materials, precise moulding conditions, and rigorous quality control ensured that the final products met the required standards for strength, durability, and ease of installation. Moreover, the use of recycled GFRP not only contributed to cost reduction but also aligned with sustainable manufacturing practices, making this approach highly suitable for industrial applications in the mining and fuel transportation sectors.

Based on the conducted tests and investigations during the project and production of joining collets using shredded GFRPs, following lessons were learnt:

The use of shredded GFRP in NOMAs epoxy based composites presents a compelling solution for sustainable manufacturing and cost effective production, particularly for non-structural and semi-structural applications. By integrating shredded GFRP into an epoxy matrix, manufacturers can achieve a balance between performance, cost, and sustainability, making it an attractive option for industries seeking to lower their carbon footprint while maintaining product functionality. However, while the environmental and economic benefits are significant, challenges related to mechanical performance, material consistency, and processing must be addressed to ensure reliable and high quality end products. To overcome these challenges, careful material selection is crucial. The quality of shredded GFRP, including fibre length, cleanliness, and uniformity, directly influences the mechanical properties and durability of the final composite. Optimized processing techniques, such as precise mixing of the shredded fibres with the epoxy matrix, degassing to remove air bubbles, and controlled curing conditions, can significantly improve the composite's overall performance and consistency. Additionally, thorough quality control throughout the manufacturing process ensures that each batch meets the required standards for strength, stiffness, and dimensional accuracy.

### Identified strengths:

- Availability of large different shredded GFRP materials,
- Comparably cheap filler for new applications,

- Possibility of control mechanical parameters by changing shredded GFRP concentration and particles size.

**Weaknesses:**

- High composition diversification of the available shredded materials,
- Due to high diversity of available materials, it is hard to control their quality and fractions content,

The comprehensive testing program not only validated the feasibility of manufacturing high performance composite joining collets using recycled GFRP but also provided a clear roadmap for scaling production. The iterative approach to design optimization and process refinement ensured that the final product met both technical and economic requirements. Moving forward, the insights gained from this stage will guide further development, including large scale production trials, long term durability testing, and field applications in industrial pipeline systems. The successful integration of recycled materials into advanced composite products represents a significant step toward sustainable manufacturing in the pipeline and infrastructure sectors.

## 10. CONCLUSIONS

The parts developed in the MC4 project and presented in this deliverable aimed at demonstrating the feasibility of manufacturing product made from recycled composites. Several composites recycling methods were developed in the MC4 project such as long term and short term methods for both glass and carbon fibre components. Each demonstrator was carefully selected so that the recycling methods and the characteristics of the recycled material was in accordance with the requirements of the part. For this reason, there is a large variety of sectors represented in the project, such as automotive, boat, aerospace, sport equipment, urban furniture or civil engineering. Demonstrators were both assessed from a technical and economical perspective in this deliverable. Moreover, they were compared with their equivalent made from virgin material so that it was possible to point out their strengths and their weaknesses.

In all the parts manufactured, process had to be adapted so that it was possible to work with recycled materials. While some processes needed only adjustments to incorporate recycled material such as the kayak, the boat roof or the bench, some needed to be completely redefined such as for the bus skirt that went from a metallic to a composite process, or the aerospace demonstrator from RTM to hot press forming.

In many processes the supply chain issue was pointed out considering the difficulty to get the recycled material in a sufficient quantity for production. Also, some products must be very carefully stored and tracked as it is the case for recycled prepreg that requires controlled storage temperatures, and a very specialized supply chain should be developed.

At a technical level, the manufactured products met the specifications of the parts, showing that the demonstrators were relevant considering their respective recycled material.