CIRCUBLADE – circular approach to resource usage based on end-of-life wind turbine blades

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Summary

Since the 1990s, the number of wind turbine blades (WTBs) installed each year has increased significantly. However, methods for handling these blades at the end of their service life have not kept the pace. With a typical lifespan of 20–25 years, the blades from early installations in the 1990s are now reaching the end of their operational life. Wind turbine blades, primarily made of glass fiber, are difficult to recycle. Repurposing them into new products is therefore a more viable approach, as it retains their value. This project focused on exploring such possibilities.

The CIRCUBLADE project investigated the potential to develop a circular solution for reusing large quantities of end-of-life (EoL) WTBs. The research covered efficient logistics, design and manufacturing, the development of a digital tool to support the circular process, and overall resource efficiency. To ensure the environmental soundness of blade reuse, a life cycle assessment (LCA) was conducted. Additionally, to gauge consumer interest, a survey was distributed to Swedish municipalities.

As part of the project's demonstration, a bridge was constructed using composite materials from recycled and reused WTBs, with the load-bearing structure made from an EoL blade. The survey indicated that Swedish municipalities are open to adopting products like the bridge, given they meet the same standards as conventional infrastructure.

The logistical analysis revealed that transportation and machinery account for a significant portion of the total handling costs, with logistics comprising up to 30% of the total project expenses. Establishing logistical hubs could improve efficiency, but transporting blades across EU countries must become easier. Currently, the classification of blades as waste rather than products poses a major obstacle to efficient cross-border transport.

To facilitate blade management, a digital platform was developed. The platform is designed to catalogue blades in Sweden and provide secure access to data needed for repurposing, such as structural details and repair history. Additional tools, including a cutting calculation tool and a routing tool, have also been integrated to streamline the repurposing process.

Finally, an LCA was performed to determine when repurposing a blade is environmentally viable.

To support actors in improving the circularity of their designs the project produced two guidelines. A Circularity Design Guideline that provides an understanding of what to think of to design a more circular product. A Sustainability Guide that highlights the gains of using repurposed products form wind turbine blades.

Content

1. Perception of the public (municipalities) about the products incorporating parts of end-of-life wind turbine blades

In the project, a survey using a structured questionnaire with 9 questions was conducted to explore the perceptions of the public (specifically municipalities) regarding new products incorporating components of end-of-life (EoL) wind turbine blades (WTBs). The survey was structured in two sections. The first section used closed-ended questions to gather basic information about the survey participants. The second section featured open-ended questions aimed at understanding the participants' needs for new infrastructure and their perspectives on using repurposed materials. This investigation proved to be a crucial step, often neglected, but anticipated to streamline the incorporation of EoL WTB products. The questionnaire was distributed to all municipalities across Sweden, with a response rate of approximately 10%. The questionnaire can be found in Appendix 1.

While the questions primarily focused on pedestrian bridges, respondents were encouraged to consider alternative applications like benches and bicycle shelters.

The survey shows that the market demand for pedestrian and cycle bridges is substantial and mainly driven by the need for durable bridges and reliable connectivity. The number of pedestrian bridges per municipality varies significantly (from 1 to 93), and the needs are consequently different. The survey also shows that several bridges are planned to be built in the coming years, and that repair is needed each year for a few individual bridges. Regular maintenance to avoid premature ageing is also very important. There are a multitude of reasons that lead to the repair of pedestrian bridges. Some of the most frequent include renovation due to moisture damage, such as wood rot or foundation settlement. Other common reasons for repair (beyond regular maintenance) include railing damage, concrete damage, minor concrete repairs, collision involving railings, repainting steel due to rust or paint flaking, general wear and re-insulation, or replacement of sealing layers.

Maintenance costs for each bridge vary significantly, ranging from SEK 5000 to 20,000 (ca 500–2000 EUR) for minor repairs and maintenance, to several million Swedish crowns for major renovations.

All respondents participating in the survey showed an interest in considering innovative solutions that allow a lower CO_2 footprint and lower maintenance costs. However, their focus remains primarily on concerns such as the cost, load requirements, and service life.

2. Sustainable business models and market introduction

In this section the logistics of using blades from wind turbines in new products and structures are analyzed. The logistics analysis provides an understanding of what the process for transforming a wind turbine blade (WTB) into a new product looks like and what challenges have to be addressed. The logistics analysis was based on interviews with experts who are involved in using second life WTBs in their business. Potential and current business cases have been analyzed and show the potential in using old blades for other applications than for producing wind energy.

2.1 Logistics and costs

One of the prerequisites to make it possible to continue using products after they have reached the end of their life is an economically sustainable logistics chain. It is therefore important to investigate how much the logistics costs of the transport of dismantled WTBs might be.

There are many aspects that will affect the cost of logistics. A list with these aspects has been developed with the help of Anmet, who has been involved in the project as an expert in turning wind turbine blades into new products and with the help of other experts in the field via interviews and questionnaires. The experts who have been helpful are Business in Wind, Kingo Wind, DSV and the University of Southern Denmark's Institute for Technology and Innovation.

The factors that need to be considered are the following: the accessibility of the blades, their dimensions and weight, the need for preparatory work before transportation, machines required for the preparatory work, the transport distance, the need for permits for handling and logistics, and the environmental aspects.

The analysis includes steps from the moment when the blades have been removed from the rotor until they have been refurbished.

A map of a circular supply chain for EoL WTB can be seen in Figure 1.

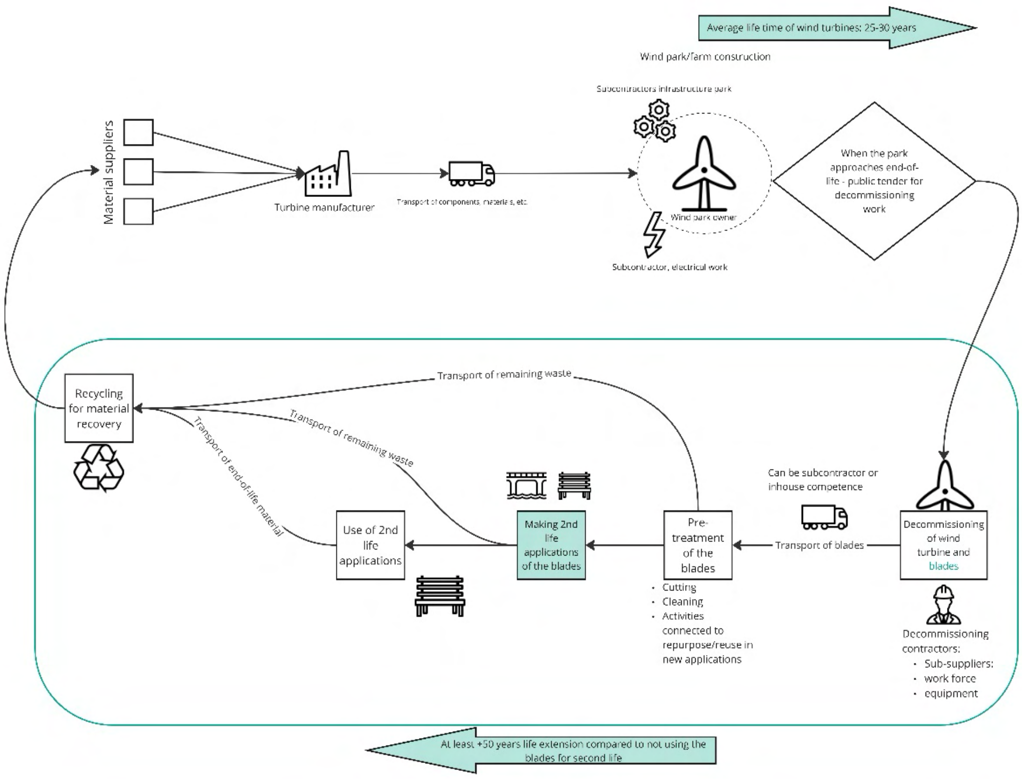


Figure 1 A Circular Supply Chain for EoL WTB.

The location of the blades

The availability of the blades affects which machines can be transported to the turbine. It is therefore important to choose blades that are easily accessible to reduce costs and time consumption.

Both according to DSV and Business in Wind, the placement of the blades affects handling and dismantling, it is advantageous to work in a field compared to the mountains[1] [2]. The blades' location affects the size of trucks that can access the blades. In some cases, modifications on the roads may be required so that it is possible to transport the blades, according to DSV. The size and load capacity of the vehicles can affect how large blades can be transported and how much the blades need to be pre-treated before they are transported. The distance to the plant where the WTBs are located will affect the price of transport.

The placement of the blades can be an opportunity for creative solutions, Figure 2 below shows how Business in Wind transports wind turbine blades using barges.

[1] Project Manager, DSV, e-mail exchange, 2024 01 30.
[2] High Level Manager, Business in Wind, e-mail exchange, 2024 02 05.

Figure 2 Wind turbine blades are transported via barges. Image: Business in Wind

Dimensions of the blades

The dimensions and weight of the blades affect the number of blades that can be transported at a time. There are limitations to how long and heavy the transports can be, and the blades may therefore need to be cut into smaller parts to be transported. How long the blades can be during transport is limited by how long a load can be before the transport requires an exemption permit.

Presently the length of the blades is not a major problem for logistical handling, due to the fact that it is mainly older wind turbines with relatively short blades that are dismantled, according to both DSV[1] and Kingo Wind.

Fieldwork and preparatory activities

The need for preparatory activities is influenced by the following factors:

- What the blades will be used for
    - Recycling

    - Reuse
    - New applications
- The conditions for long transports
- Possibility for storage

Cutting the blades in the field is costly. It must be considered whether the blades should be cut on site to facilitate transport, or whether they should be transported as a whole so they can be handled in a controlled environment, according to DSV[1] and Anmet[3].

If the blades are transported as a whole, a crane is required that can lift an entire blade, and a truck to transport the blade. The blade is lifted onto the trailer, attached to the truck's trailer and driven away. The lifting takes a few minutes, but transporting the crane and preparing it for lifting is time-consuming and must be taken into account, according to Kingo Wind and DSV[1].

Both Anmet and the other experts try to minimize fieldwork to reduce costs, as well as to reduce the impact on the environment[3]. If the blades are to be cut on site, it requires a machine that can saw the blades, and a larger workgroup compared to only lifting a blade.

Large amount of dust is created when cutting the blades, which is easier to handle in a workshop than in the field. In cases where Anmet cut blades on site, they use filter mats on the ground and a tent that covers the work surface, to control the spread of dust[3]. DSV has also developed a system to be able to cut blades with minimal impact on the environment[1]

If cutting the blades is required, the experts are exploring different methods to cut the blades on site. All the solutions should increase the volume that can be transported.

Transport

Anmet and several experts have reported that recently, the cost of transportation has increased[3]. This has led to being more economical to carry out larger parts of the work on site to avoid costly transport. On each occasion, it is a consideration whether the blades should be cut on site to optimize transport.

The costs of transport vary greatly, according to all the experts it is difficult to give a price estimate for how much it can cost to transport the blades[1 2 3].

In Sweden, it is possible to transport a load that is 30 meters long without a derogation decision, which limits the length of the blades to 30 meters without applying for an exemption permit.

[3] Project manager, Anmet, e-mail exchange, 2023 10 27.

Machinery and equipment

Machines required on site for preparation and transport vary depending on the need for preparation and the size of the blades.

If the blade is to be transported completely, it requires a crane truck with a capacity of 80 tons/meter for a blade that is 23.5 meters long, according to Kingo Wind. In cases where the blades are cut on site before being transported, a lighter crane truck would be suitable. Figure 3 below shows how a cut blade is lifted to be transported on to processing.

To cut the blades on site, a cutting machine is required. Anmet uses two different cutting machines, depending on the number and size of the blades. For small volumes, a portable power cutter is sufficient. For large volumes, Anmet has developed a band saw that is mounted on an excavator.

Figure 3 A cut blade is lifted to be transported. Image: Anmet

The choice of vehicles used to transport the blades from the wind farm depends on whether the blades are to be transported whole or cut. To be able to transport the blades whole a low-loading semi-trailer can be used. When cut blades are to be transported, a walking floor trailer is suitable, according to Figure 4. A walking floor trailer makes unloading easier and makes it possible to load several pieces in each load.

Permits and requirements from authorities

To dismantle and transport WTBs, permits from authorities are required. The permits vary between countries [1, 2].

In Sweden, the Swedish Energy Agency has developed a guide on what applies to the dismantling of wind power in the "Guidance on the dismantling of onshore and offshore wind turbines". The permits and regulatory requirements that may affect the handling of the blades are following:

- A demolition permit or notification is required when dismantling wind turbines.
- Offshore wind power requires a permit or notification.
- Application for transport exemption if required.
- Permit or notification of the shipment of hazardous waste.

Figure 4 Cut blades loaded on a walking floor trailer. Image: Anmet

The Swedish Energy Agency's guidance makes a detailed review of what should be considered; for more detailed information the reader is referred to[4].

Within the EU, a permit is required to transport waste between countries. According to both Anmet's and DSV's experience, it can take from three months to a year to obtain such a permit.

Storage

Storage of materials can occur at several stages of the process. When the blades are shipped for cutting, they may be stored before being transported for processing. They may need to be stored before they are to be converted to new products, according to Kingo Wind, Anmet and DSV. Storing WTBs can require large areas and premises,

[4] The guidance can be downloaded free of charge from the Swedish Energy Agency's web shop: [Energimyndighetens webbshop (a-w2m.se)](a-w2m.se)

and it can be expensive if the blades need to be stored for a long time. It is therefore important to take the storage of the material into account when planning the project.

Future challenges

In the future, there may be greater problems in shipping and taking care of WTBs. At present, larger wind turbines are being developed at the same time as offshore wind power is increasing. Currently, it is older generations of wind turbine blades that are dismantled and used to build new products, and these are rarely offshore.

The transport that was carried out during the project included a 23.5 meter long blade. At sea, the blade length can be over 100 meters (Siemens Gamesa, n.d.). Transporting these giant blades implies greater challenges in terms of crane requirements, size of transport trucks, time and effort in the field for cutting and preparing for transport. Offshore wind power will also pose several challenges for efficient logistics of EoL WTBs, with high costs, where opportunities for on-site cutting to streamline transport are significantly limited. Offshore wind logistics may be a topic worth exploring in more detail going forward.

The increased size of the blades provides new possibilities for second-life applications. These large blades are stronger than today's small blades, which provides opportunities for new and innovative products that can be made from EoL blades.

Activities for the handling of end-of-life wind turbine blades for reuse

According to the information provided by Anmet, Kingo Wind, DSV and Business in Wind, a list of activities has been compiled which can be found in Table 1 below. A more detailed table where times and costs are also available is available in Appendix 2.

According to the information provided by the experts, planning the transport is very time-consuming. This also applies to the preparatory activities, and logistics for all the machines and equipment that must be in place to enable environmentally friendly work. The actual cutting of the blades and the effective time for lifting only takes a few minutes, according to DSV and Kingo Wind. But setting up the power cutter and cranes on site can take up to a whole day, which underlines the need for good planning and logistics.

In this project, the lifting of the rotor onto the ground has not been included since it is considered to be part of the dismantling of the entire wind turbine. However, it is a large part of the work effort, according to Kingo Wind and Business in Wind, it requires very large cranes, and several days of work effort to dismantle the wind turbines. According to Business in Wind, it can take 130 – 600 man-hours and 10 – 36 crane hours to dismantle a wind turbine, which can be costly. This large variation shows that costs will vary greatly depending on the time the work takes.

Table 1. Activities of end-of-life wind turbine blades for reuse.

Main activity	Sub activity
Preparatory activities before the start	Application for national permits Applying for international permits Logistics planning
Disassembly / Preparation	Preparing area to minimize environmental impact Preparing saw Separate the blades from the rotor Cut blades into smaller pieces if necessary Lifting small pieces on a forklift Lifting whole blades on forklifts
Transport	Adapt infrastructure as needed Transporting whole blades Transport of cut blades
Facility for handling for further transport	Cut blades into smaller pieces if necessary
Transport	Transport of cut blades
Further processing from blade to product	Processing Manufacturing product Waste management

2.2 Extended life of WTBs

The most circular and resource-efficient management of WTBs is when they continue to produce electricity. This requires good maintenance of the blades. WTBs are subject to strong winds, rain, hail, and even lightning, so there is a lot that can wear down the blades. Regular inspections of wind turbine blades are carried out, which helps to increase their service life. From the moment a wind turbine has reached the end of its planned life, it is possible to continue using the wind turbine, provided that it is ensured that they meet all safety requirements. This is possible with a so-called RUL (Remaining useful life assessment), which ensures that the entire wind turbine, including the blades, has a sufficiently good strength for continued use.

Eventually the wind turbines will be dismantled, due to the need for their upgrades or the end of their primary life. If a wind turbine needs to be upgraded, it does not mean that it can no longer be used. It is still possible to sell it to actors with other needs. It eliminates the need for new manufacturing and does not rely on recycling processes to handle the wind turbine blades, which are currently not fully developed for the continued use of the material (Beauson et al., 2022). There are several different companies that today work with selling used WTBs and also other components of the wind turbine such as Deutsche Windtechnik, Surus and RePowering Solutions. There are also online marketplaces for the sale and purchase of wind turbine blades where players can both look for and offer wind turbine blades such as WindTurbines-MarketPlace[5].

Within the EU, Ireland is pointed out as an example of a country where Swedish wind turbine blades have been installed for continued use when the Swedish wind farms are to be upgraded, so-called "repowering". There are various factors that can affect this, but one of the reasons is electricity prices. In Ireland, electricity prices are high, while the Irish government subsidizes the expansion of small-scale wind power. These conditions make it possible to resell WTBs when they no longer fulfil their purpose in Sweden. At the same time, there are examples of smaller Swedish players (such as farmers) buying older wind turbines from the Netherlands to produce their own electricity (Juntikka et al., 2018).

Currently, 85% of dismantled wind turbines go on to the secondary market, and 15% go to recycling or other handling. As described earlier, wind turbines can be replaced prematurely to upgrade the farms and optimize electricity production. These wind turbines have been easy to sell to players who want quick access to cheap wind turbines, and to players where there are restrictions on the maximum height of the wind turbines. But now the pace of development has slowed down and the need for "repowering" will not be the same in the future. Therefore, it is likely that wind turbines that go to the second-hand market will decrease, and a larger share will go to recycling (Gauderis and Sverijns, 2022).

[5] https://windturbines-marketplace.com/

3. Business cases

There are various opportunities to create value from EoL WTBs through reuse. The opportunities can be divided into two categories: resale of wind turbines, or production of new products from EoL blades. Below we describe business opportunities based on experiences from our project.

3.1 Reselling of WTBs

According to what was described above, it is possible to prolong the time that the blades are used by selling them on to other players.

There is an established market for the sale of WTBs, and complete wind turbines. Both within Sweden and Europe, but also in other parts of the world.

3.2 Manufacturing of new products

Anmet is an established player who manufactures products from EoL WTBs: bridges, interior fittings for offices, urban furniture and other infrastructure-related products. Anmet has also been involved in building the first bridge made from EoL WTBs in the world (Anmet, n.d.).

Fosieplast and Composite Design have also started to establish themselves in this market in Sweden through the manufacture of a bridge as part of this project and other residual products of composite materials, e.g. in the RECINA project.

The products created vary in size and material requirements. Some products require large parts of wind turbine blades, and some the whole WTBs.

Large products such as bridges have the potential to become a long-lasting product and replace the need to manufacture bridges from primary raw materials such as concrete. Based on the market survey conducted in the project among all of Sweden's municipalities, there was a great interest in innovative and sustainable bridges made from EoL WTBs. The study showed that more knowledge about the material's properties and what opportunities exist with bridges made from EoL WTBs would be needed.

There is also the possibility of creating other infrastructure, such as noise barriers. There is a great need for noise barriers in Sweden in the future and it would be optimal to use the WTBs for that purpose. The advantage of using WTBs to manufacture noise barriers is that it is a simpler product to manufacture, with simpler requirements for the design. This means that there is a greater opportunity to use the WTBs in mass production compared to the bridges.

Using the wind turbine blades as a building/construction material is also possible, as the project partners, Composite Design and Vattenfall have shown. In Lund, a parking garage is being built where wind turbine blades will be used as façade material and that creates a valuable product from the WTBs and avoids the use of primary raw material.

There are also other initiatives such as building playgrounds out of wind turbine blades, which BladeMade in the Netherlands has done. The Scottish ReBlade has also used parts of wind turbine blades to build sun visors for car charging stations. This shows the possibilities that exist with using EoL wind turbine blades as an input raw material in various products.

4. Design

According to the Riksrevisionen's report on the handling of EoL wind turbine blades, no work is currently underway in the EU to develop eco-design requirements for wind turbine blades (Riksrevisionen, 2023).

There is also no such work underway regarding other products that contain a significant proportion of plastic composites. However, negotiations are ongoing regarding the introduction of a new EU regulation on eco-design for sustainable products. The proposal for a new regulation means that requirements for eco-design will be placed on virtually all categories of physical goods that are permitted on the EU market. The requirements are proposed to include reusability, repairability, content of harmful substances and expected amount of waste from the products. The proposal also includes the introduction of digital product passports (European Commission, 2022).

Wind turbine blades are currently not a product group for which special eco-design requirements are prioritized, but it is not excluded that that assessment may change in the future. In our project we have developed simple guidelines for design for circularity, where many principles could also be applied to wind turbine blades. The guidelines are included in the Appendix 3.

In the project we have also developed a "Sustainability Guide" that is intended to be shared with the municipalities, organizations and companies to raise the awareness about circularity, reused material from EoL wind turbine blades and its advantages, as well as to show examples and innovative solutions made from this valuable material. The Sustainability Guide is included in Appendix 4.

5. Certification processes for repurposing of EoL WTB

5.1 Verification prior to repurpose EoL WTB – Status

To be able to repurpose EoL WTBs at industrial scale, there is a need to develop “certification supported mechanical processes” (cutting and shredding) to allow and increase the circulation of EoL FRP in new products. Robust certification processes, adapted to the end-product complexity, are the cornerstone for an increased sustainable management and repurpose of EOL WTBs. No standard process is however available today.

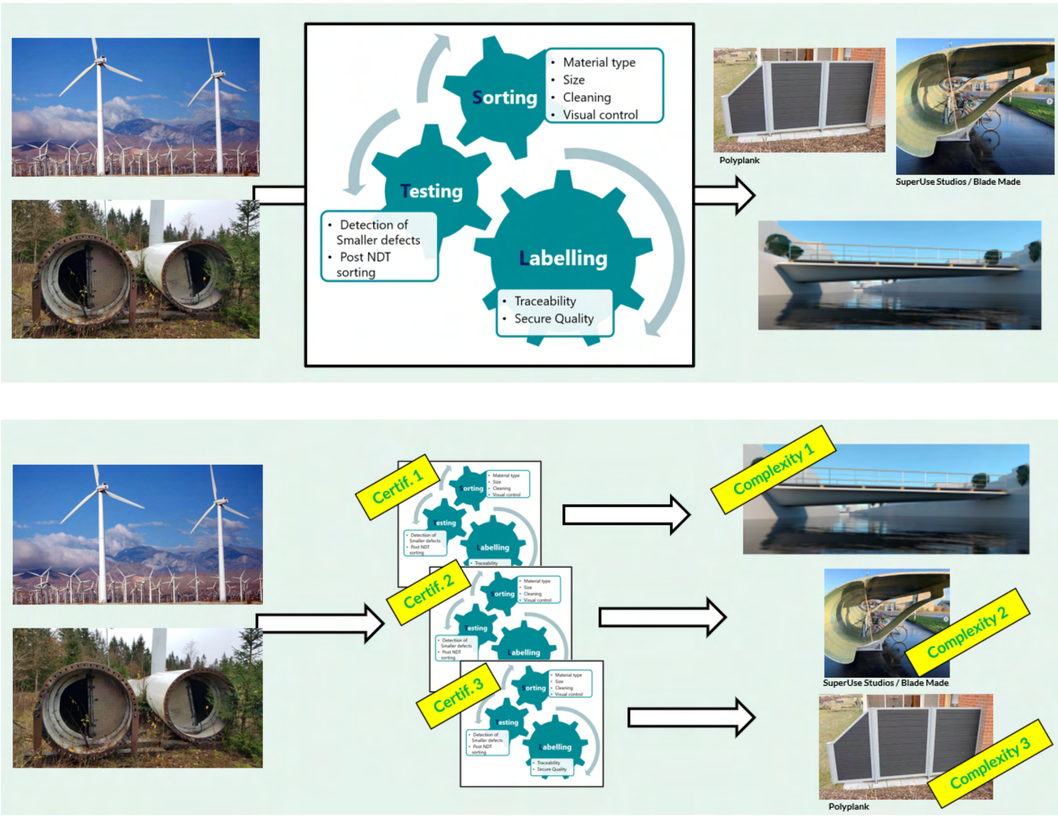


Figure 5 Robust certification processes, adapted to the end-product complexity, should be developed to allow an increased repurposing of EoL WTB into new products.

Several questions need to be addressed while developing these certifications processes:

1. Need to understand the market: which potential products will most probably be manufactured with EoL WTBs? What validation process will be needed?
2. Validation and certification processes have been developed for specific composite structures. Can they be used in some extent with EoL WTBs?
3. What equipment is needed?
4. Can data from the blade maintenance history help predict the blade condition at EoL and thereafter accelerate the validation process?

Several challenges have been identified:

1. Understand the value that can be recovered and chose the best process in relation to the need for the next application.
2. Develop several certification processes where sufficient information is available for well-defined applications (industrial needs and requirement must be defined).
3. Create FRP waste recovery infrastructure in order to enable the FRP waste stream to reach the new industries involved in the recycling, validation and manufacturing processes.

Potential products made of EoL blades

As mentioned briefly earlier in the report, several products, prototypes and concepts made of EoL blades have been developed and manufactured during the last decade. Most of the projects behind these pioneering achievements have been carried out in Europe and in the US.

The links to some relevant references where several concepts are presented are given under:

- Rewind project, concept catalogue (2022): https://static1.squarespace.com/static/5b324c409772ae52fecb6698/t/636bd07125aeb5312a8e320e/1668010099748/Re-Wind+Design+Catalog+Fall+2022+Nov+9+2022+%28low+res%29.pdf

- Rekovind 2, project report (2023): Digital platform for management of EoL wind turbine blades: Rekovind 2 - WP2: https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1780208&dswid=4224

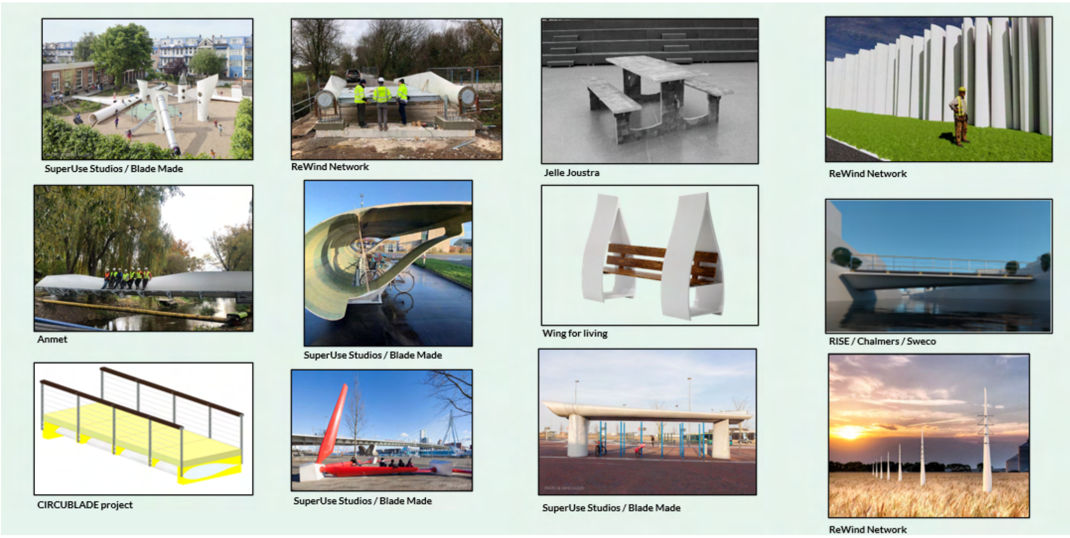


Figure 6 Examples of potential products made of EoL WTB.

A preliminary complexity rating has been done in order to have a first insight on how to classify the products shown in Figure 6 in relation to the certification process to carry out on the repurposed WTB, see Figure 7. The level of complexity of the product to be built with repurposed EoL blades, and the requirements from regulatory standards, should dictate the level of complexity of the certification process to verify the quality of the EoL WTB.

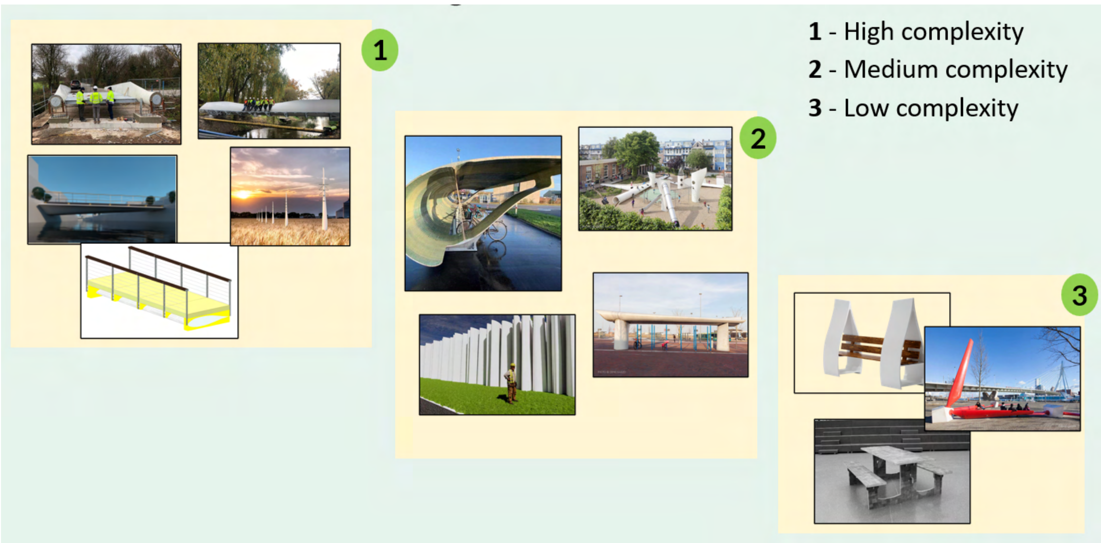


Figure 7 Complexity rating.

What processes exist today:

1. Process implemented for the bridge in Cork, Ireland (ReWind network Ruane et al., 2022)
   - LM blades, 13.4m long.
   - Manufactured 1997 – 27 years old.
   - 2 blades recovered and tested to be used as girder for a new pedestrian bridge, see Figure 8.

Figure 8 One of the WTB used for the girder of the pedestrian bridge in Cork (Ruane et al., 2022).

   - Material tests (volume fraction and laminate architecture). Resin burn out tests (***ASTM D2584***).
   - Mechanical tests (tension ***ASTM D3038*** and compression ***ASTM D3410***) at multiple location.

- Full-scale flexural testing of a 4m section (load-deflection, ultimate capacity, stain history, failure mode)

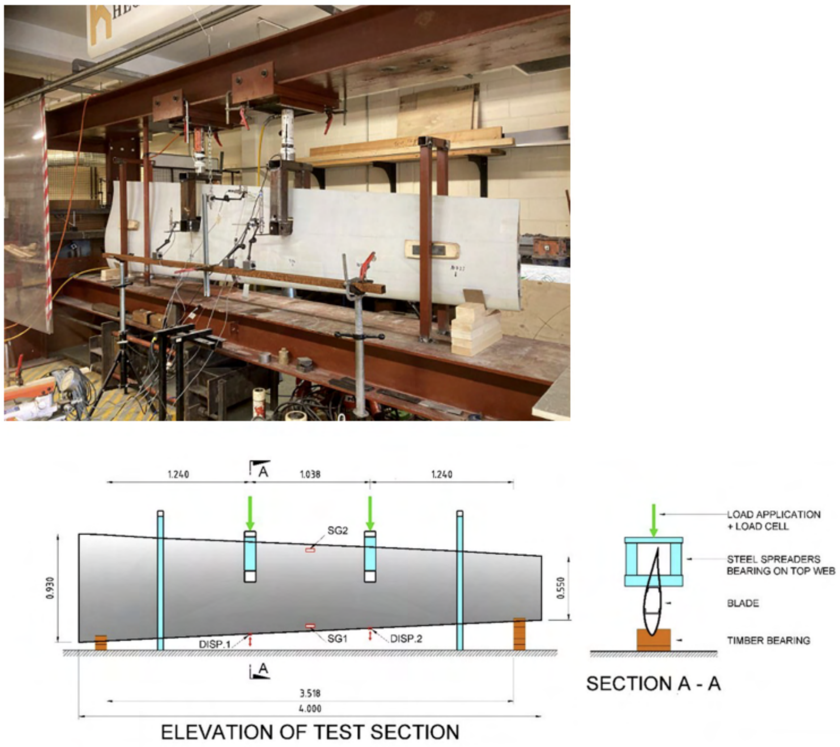


Figure 9 Test rig and test set-up used in the ReWind project (Ruane et al., 2022).

From the bending test of the WTB sections, it was observed a separation of the shear web flanges from the skin at the bottom (LE: Leading Edge) shear web splitting of the bottom (LE) of the blade half-shells in the area of the supports.

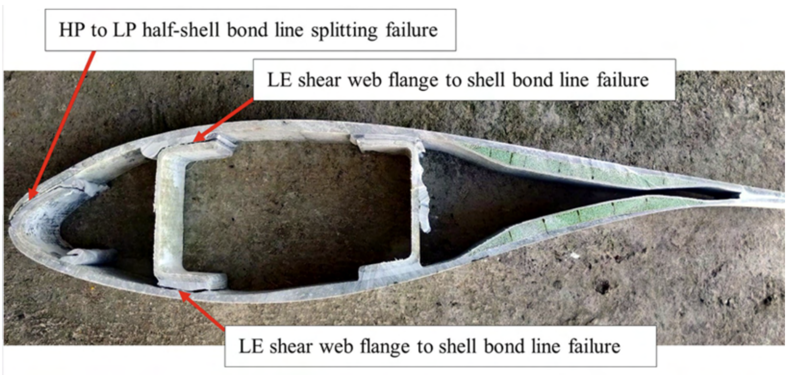


Figure 10 Results of the bending tests from the ReWind project (Ruane et al., 2022).

From the tests carried out in the ReWind project, it was concluded that the FRP material is still in excellent condition and that the blade has the strength and stiffness in flexure to serve as a girder.

Full scale mechanical testing of the bridge was also carried out for the final verification of the bridge load bearing capacity.

Figure 11 Full scale testing of the Cork bridge ReWind project (Ruane et al., 2022).

Process implemented for the bridge in Poland (Anmet)

In Poland, in December 2021, Anmet installed a pedestrian bridge over a river in Szprotawa. The main girder of this bridge is made of 2 decommissioned wind turbine blades (LM23), which make this bridge the first of its kind in the world.

The bridge total length is 22m, with a free span between supports of 16m.

The blades originated from a decommissioned wind farm in Germany, and were subjected to several mechanical and engineering tests before being cut and repurposed as the primary support structures for the pedestrian bridge. These tests were carried out in collaboration with Poland's Rzeszów University of Technology.

Figure 12 Anmet pedestrian bridge in Poland.

Both static and dynamic tests were done on the blade prior to repurposing them as girder on the bridge application.

The pictures shown under are extracted from Anmet website (Anmet b, n.d.) and show the blade on the test rig during the mechanical testing.

Figure 13 Bending test of the repurposed WTB for pedestrian bridge application.

Non Destructive Testing (NDT)

Each NDT method offers their own advantages and limitations in terms of ease of use / inspection time and resolution/quality of the results produced for the chosen application (wind, aerospace, or marine sectors). Amongst them, **thermography** and **ultrasonic testing** have been shown to be accurate methods for the characterization of the most common sub-surface damages in GFRPs (Towsyfyan et al., 2022).

Thermography, which is based on the analysis of the variation of temperature decrease upon external heating on a structure, is a relatively quick NDT technique in comparison to ultrasonic testing. It is a contact less method and it is well suited for the inspection of larger area, which makes it attractive for a flawless inspection method during production. However, thermography is less sensitive in characterizing deep defects below the surface, and the technology is somehow less mature than ultrasonic testing. Thermography has been used successfully in the aeronautic and wind industries, and to some extent for the inspection of GFRP hull boats (but only off production line).

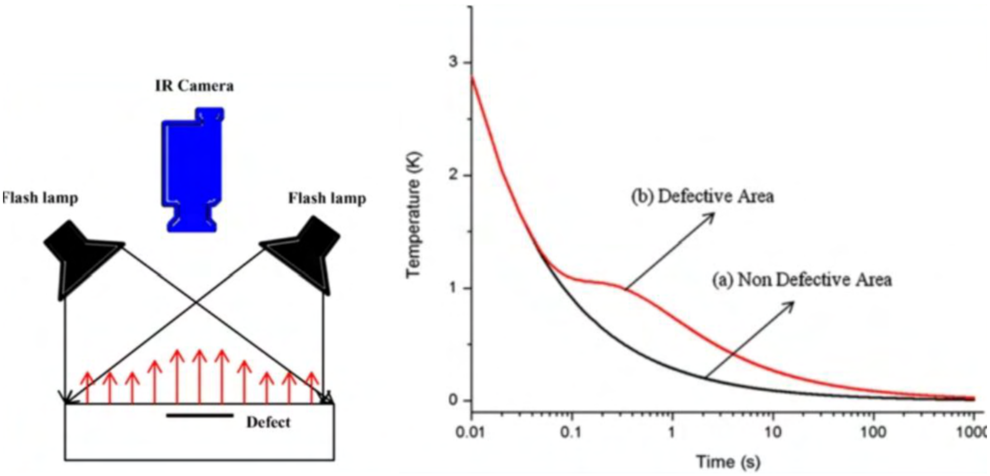


Figure 14 Thermography for detection of defects (Klöckner, 2021).

Ultrasonic c-scan equipment can be used to verify locally the structural integrity of a composite structure such as a blade. Ultrasonic testing has been used successfully for the inspection of GFRP boats and wind turbine blades and is today a well-established method for aerospace grade composite structures. Ultrasonic testing requires a coupling media between the probe and the surface under inspection. It can detect defects through the entire thickness of the structure and resolve even the smallest flows in the material.

Figure 15 Ultrasonic C-Scan on a GFRP part (Photo: Thomas Bru).

The method of **effectively combining multiple NDT** techniques into a multi-scale NDT technique has shown being efficient. Multi-technique NDT have been implemented on a lab scale to correlate damage development events and cross-validate the results obtained from each technique. It has been shown the synergy obtained when effectively combining multiple techniques. Faster, smarter, multi-scale inspections can be achieved by taking advantage of each method. Finally, the latest NDT trend for industry with higher volume production rate is automation. Today, it is possible to inspect large composite structures in a flexible way and in a reasonable time with the help of automatic robotic arms (Chaki et al., 2015).

Figure 16 Combining several NDT techniques with automation can help accelerate the detection of damage.

Blade scanning for CAD model generation

In many cases where a decommissioned wind turbine blade is repurposed, access to the original CAD models generated by the blade OEM several years before are not available. However, to generate CAD models of a decommissioned wind turbine blade, reverse engineering methods can be used.

A method that has been used in the ReWind project is the LiDAR scanning method (see Figure 17).

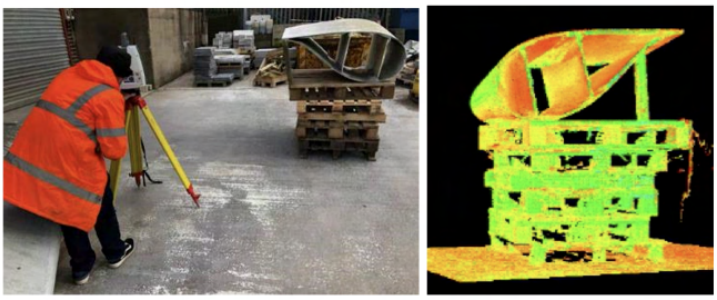


Figure 17 LiDAR scanning of a WTB section (Ruane 2023).

LiDAR, short for "Light Detection and Ranging," is a remote sensing technology that uses light in the form of laser pulses to measure distances. LiDAR systems typically include a mechanism for rotating or scanning the laser in various directions. This allows the system to capture distance information at different angles, creating a point cloud of data. As the Lidar system scans across an area, it collects numerous distance measurements, resulting in a dense "point cloud." Each point in this cloud has spatial coordinates (x, y, z) that represent its position in three-dimensional space.

The point cloud can be processed to create 3D models. This involves removing noise, aligning points, and reconstructing surfaces. Specialized software tools are used to visualize and manipulate these point clouds, allowing for detailed modeling of objects, landscapes, buildings, etc.

Can maintenance history data accelerate the validation processes for EoL blades?

During the lifetime of a blade, a large amount of data is generated. It starts with the blade manufacturers (blade CAD models, material content, blade structure), and then during operation data is also generated by the turbine operator and by the maintenance companies (blade monitoring and repair) – see Figure 18.

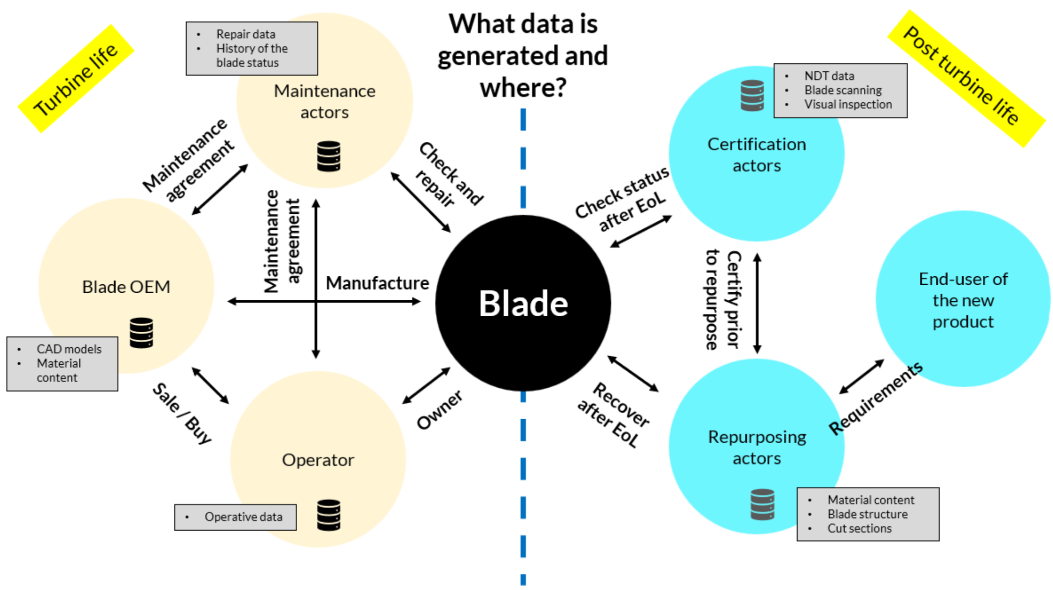


Figure 18 Estimated data generated for a blade during turbine lifetime and post turbine life time.

All this data generated during a 20 years service life (in average) could potentially have a value for actors that will repurpose the blade after it is taken down from the turbine. It is clearly of paramount interest to know the history of the EoL WTBs to accelerate their sorting process (good/medium/bad blades), and to classify them even before they are taken down.

However, the current situation is that the connection between actors generating data during the service life as a blade on a wind turbine, and actors repurposing the blade after it is taken down, is very limited or non-existent.

By bringing awareness to these actors on the value of all this existing data, a beneficial effect is foreseen, both **before (added value to existing data)** and **after (access to blade data for efficient EoL management)** the decommissioning of the blades.

5.2 Case study: NDT of the blades used for the pedestrian bridge concept

The wind turbine blade model used is a NWP28.3 ATV blade manufactured in France (early 2000). The blade is 28.3 m long, with an approximately 4 m long rotating tip (air brake). The section considered in this work is the 6 m long section after the tip (See Figure 19).

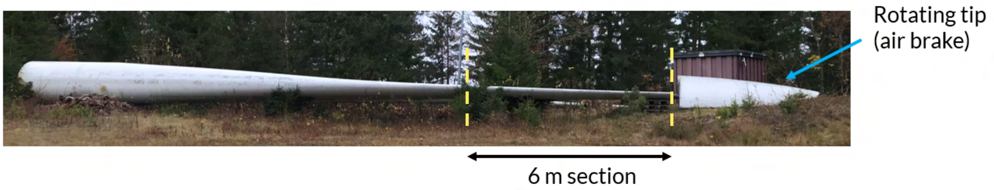


Figure 19 WTB section used for the pedestrian bridge prototype in CIRCUBLADE.

A preliminary visual inspection was done after the cutting of the blade, and the structural integrity of the blades looked fine. However, due to the nature of the material (GFRP), it is important to check for possible internal damages nonvisible from the outside. For that purpose, NDT was also performed on the WTB section.

Figure 20 WTB section at Composite Design facilities after cutting and transport.

NDT procedure was carried out on a smaller section than the one used for the bridge girder. The objective was to demonstrate the importance of NDT as a verification of the condition of the blade structure.

We have been using in a first place a point ultrasonic scanning equipment (OLYMPUS Epoch 650), with a transducer of 1MHz.

Point scanning NDT equipment is used on composite structures to detect and analyze defects at specific points through the material's thickness. By placing a transducer on the surface, this method allows for precise inspection of areas directly beneath the sensor, providing detailed data on internal conditions such as cracks, delaminations, or voids in the glass fiber composite structure.

On Figure 21, we can see that signal is producing a back echo returning a thickness of 5.49 mm at the location where the transducer is placed. Since no defect is present, this corresponds to the total thickness of the laminate.

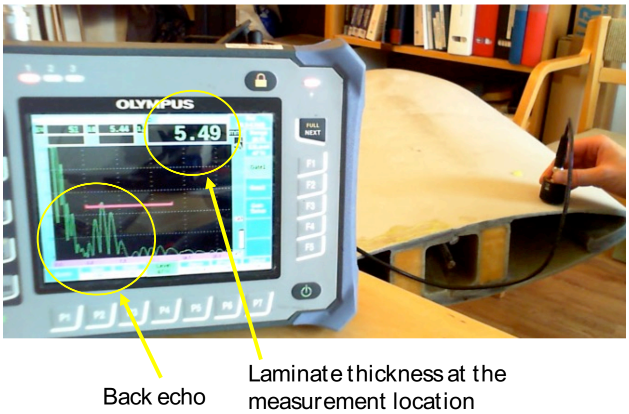


Figure 21 Set-up for NDT procedure and main reading from the Olympus display.

Using a sharp steel tool, we introduced a defect in the form of a delamination at the edge of the blade to show how this defect can be detected using the Olympus ultrasonic equipment (see Figure 22).

Figure 22 Introducing a delamination in the laminate.

Figure 23 shows the results from scanning the area where delamination was induced, both before and after. On the left (undamaged laminate), a thickness of 5.49 mm was measured, which represents the full laminate thickness at that specific location, indicating no defects. The ultrasonic signal's back echo was returned upon reaching the opposite side of the laminate. On the right (damaged laminate), the echo is returned after traveling 2.9 mm, corresponding to the position of the induced defect.

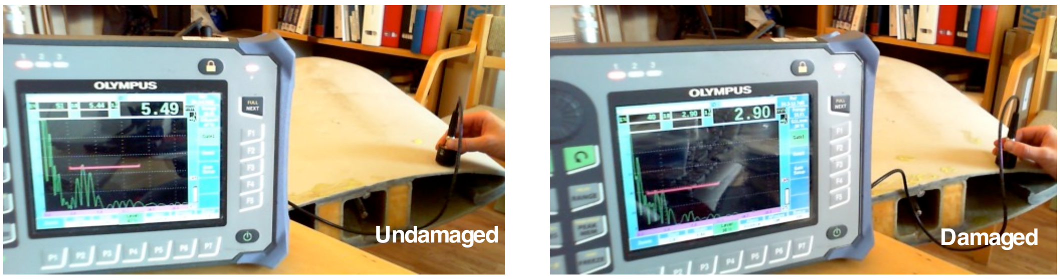


Figure 23 Detecting delamination in the blade section.

5.3 Conclusion

- The repurposing of blade at scale will require the establishment of several certification processes adapted to the complexity/requirements of the product made of decommissioned blades.
- There are no existing processes for a general validation of EoL composite structures. The processes that have been found are either specific for a specific product (e.g. composite cylinders (Hexagon Ragasco 2013)) or established for a unique structure (e.g. pedestrian bridges in Poland and Ireland).
- The certification processes should be based on 3 main steps: Sorting, Testing, and Labelling the blades.
- Several different equipment can be used to perform these tasks. One important task is related to the assessment of the remaining mechanical properties of the EoL Blades. For that purpose, Non-Destructive Testing (NDT) like ultrasonic testing and thermography, combined with mechanical tests and visual control, are expected to play an important role.
- A large amount of data is generated during the lifetime of a wind turbine blade, and a large amount of data is expected to be generated/needed for repurposing after the blade is taken down from the turbine. Knowing what data exists, and its accessibility, is foreseen to be an enabler to accelerate and ease the repurposing process.
- The certification processes that will be established are expected to significantly rely on data. Therefore, a secured and accessible database will need to be created to support the blade certification delivered by certification actors.

6. Concept design

6.1 3 concepts design in focus

Three different case studies were conducted on repurposing wind turbine blades (WTBs), each utilizing a distinct method based on the specific technical requirements of the new products. In the first case, a section of a WTB was repurposed as a girder for a pedestrian bridge. The decking system for this bridge was made from decommissioned composite pipes and sandwich panels, with over 95% of the materials used being waste glass fiber-reinforced polymer (GFRP).

For the second and third case studies, 67 WTBs of the LM 23.5 type were retrieved from a wind farm that was decommissioned during the project. These blades were divided into two segments to maximize their reuse and minimize waste, aligning with the waste hierarchy principles. The first segment, comprising the 10.5 meters from the blade tip, was repurposed into façade elements for a car park building. The remaining 13-meter segment, which included the largest and heaviest part of the blade, was used to develop noise barrier walls for road and railway applications.

Figure 24 and Figure 25 illustrate the case studies examined in the Circublade project: a short-span pedestrian bridge where a WTB section was repurposed as a girder, a car park building featuring wall elements made from WTB sections, and a noise barrier wall constructed from WTB sections.

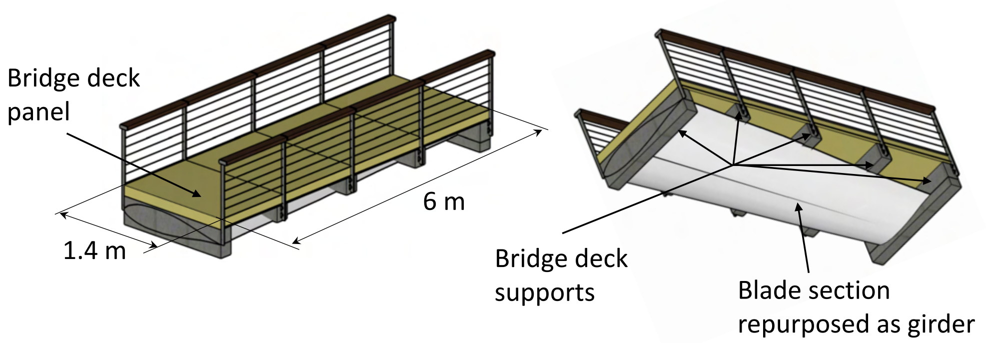


Figure 24 Case studies of EoL WTBs repurposing in Sweden: short span pedestrian bridge (illustration, main components, and dimensions).

Figure 25 Case studies of EoL WTBs repurposing in Sweden: façade elements for car parc building (left) and noise barrier (right) (pictures from Lloyd's arkitektkontor, Sweden).

6.2 Noise barrier and facade elements

The case studies on façade elements and noise barriers, illustrated in Figure 25, focused on the efficient cutting and repurposing of EoL WTBs. The blades were sectioned to extract parts suitable for each application. The heavier and more robust 13-meter root section was utilized for the noise barrier design, while the lighter and thinner 10.5-meter tip section was adapted for the façade elements, as shown in Figure 26.

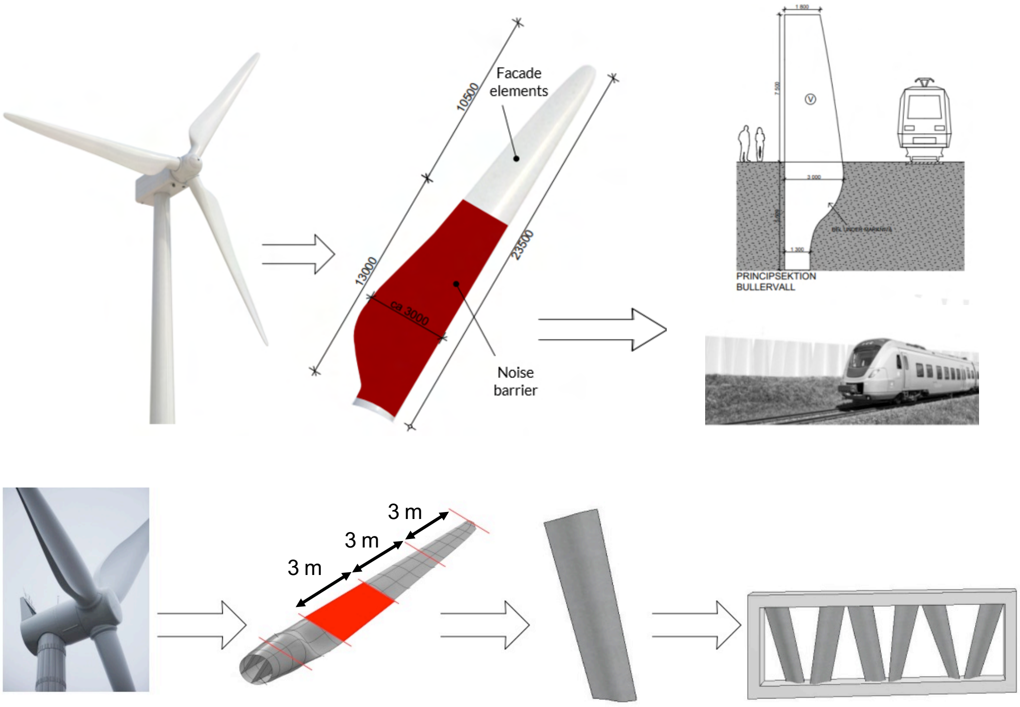


Figure 26 Case studies of EoL WTBs repurposing in Sweden: optimized cutting of the blades for repurposing as façade elements for car park building and noise barrier (pictures from Lloyd's arkitektkontor, Sweden).

The noise barrier and façade element case studies are still in progress, but at different stages. The noise barrier concept is currently under discussion with a potential end-user, with ongoing evaluations concerning procurement processes and technical performance, particularly regarding the noise insulation property. Meanwhile, the car park building concept has advanced significantly and is expected to be constructed within a year in Lund, Sweden. Approximately 170 WTB sections, each 3 meters long, will be used for the building's façade.

Creating noise barriers from WTB has great potential to utilize large amounts of decommissioned blades. The Swedish Transport Administration (Trafikverket) has more than 40 projects where they intend to build noise barriers in the coming years to minimize the noise from roads and train tracks (Trafikverket, 2024). By creating a standardized and modular method of creating noise barriers from WTB could thus be a solution to using decommissioned WTBs at scale.

To be able to use WTBs as noise barriers the must comply with the standards for such products, as is defined in ISO standard 10140-2:2021. Specifically for Sweden they must fulfill SS-EN 1793-2:2018. If they are to be built for the Swedish Transport Administration, they must also fulfill their requirements on aesthetics- and technical requirements as well as on road safety (Trafikverket, 2022).

The first step in commercializing noise barriers form WTBs is therefore to perform the required tests to make sure that the product fills all the requirements. As well as developing methods on how to produce a modular noise barrier that can be cost effective compared do current products on the market.

Other actors have been looking at similar solutions and found that noise barriers from WTB can be feasible. Blade Made in the Netherlands were involved in a study at TU Delft, that perform a numerical analysis that showed that WTB could be suitable as Noise Barriers (Przespolewski, 2022). They have also started a project to build a test facility see how the withstand Dutch regulations for noise barriers (LinkedIn, 2024). A similar idea was developed in a research project in Poland. Where parts of the blade were cut into smaller pieces to create a larger noise barrier element. The project found that the noise barrier made from parts of WTB can withstand the requirements of a noise barrier (Broniewicz, 2024). A project partner, Anmet, has also investigated noise barriers made of WTB. They found that the noise barrier could have a negative effect on the noise quality, instead of reducing it. Which makes it clear that further studies on the topic are required to make sure that WTB are suitable for noise barriers.

6.3 Pedestrian bridge: Design and limitations

The pedestrian bridge case study involves a short-span bridge where a section of an NWP28.3 ATV wind turbine blade (WTB) was repurposed as a girder. This WTB measures 28.3 meters in length, with a 4-meter rotating tip serving as an air brake. The section used for the bridge was a 6-meter section cut from just beyond the tip (see Figure 19).

The NWP28.3 ATV WTB has an internal I-beam structure (One longitudinal spar, composed of 2 spar caps and 1 shear web, adhesively bonded to the skin of the blade), see Figure 27. It is made of both Glass Fibre Reinforced Polymer (GFRP) and Carbon Fibre Reinforced Polymer (CFRP).

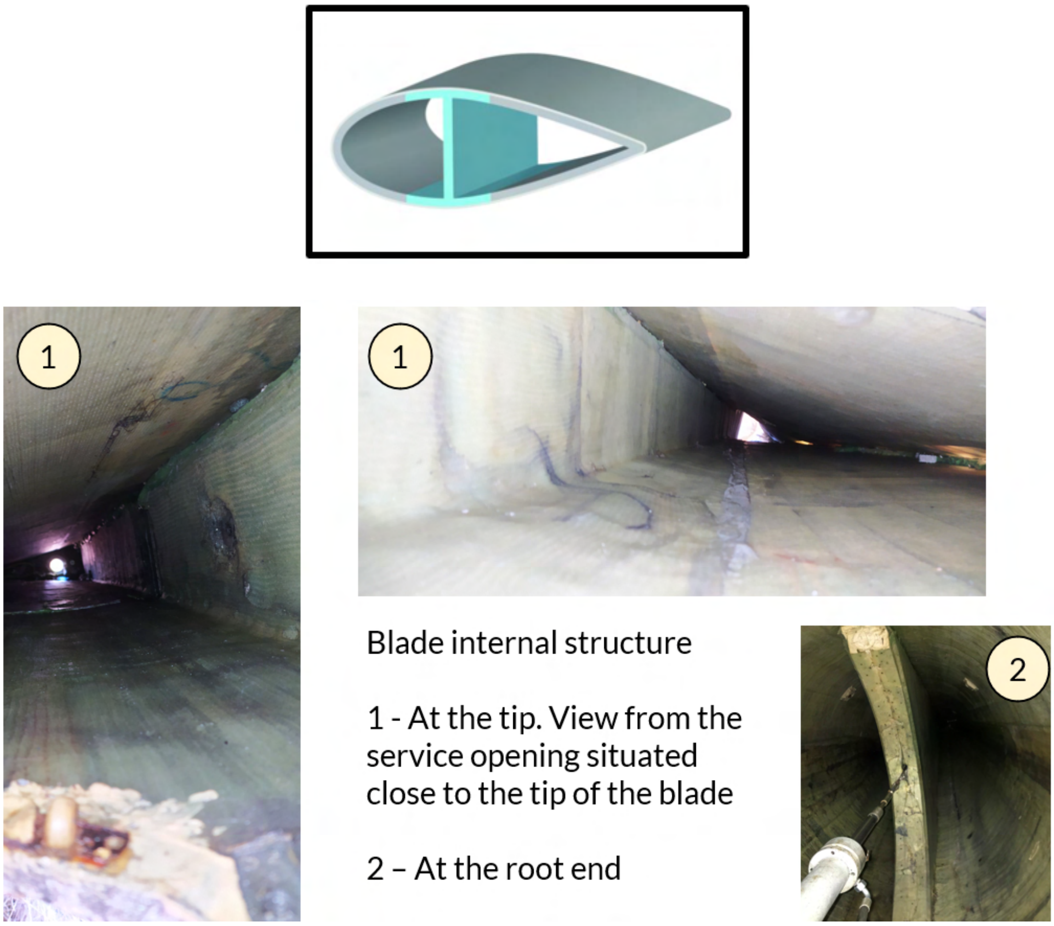
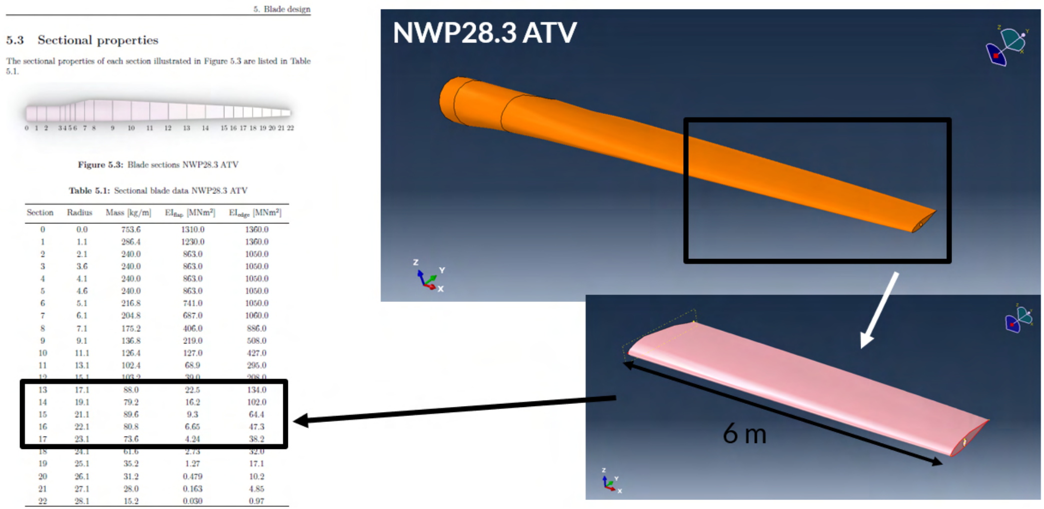


Figure 27 NWP28.3 ATV WTB internal structure (Photos: Alann André).

Detailed sectional data along the blade's length, obtained from the manufacturer in a previous study (Dahlén and Härnborg, 2021), were utilized for the structural analysis. Preliminary finite element (FE) models were created using the commercial software Abaqus (ABAQUS 2024) to examine the bridge's deflection. The design load was based on Traffic Class 4 (SS-EN, 1991), with live loads of 2000 N/m² and dead loads (including the WTB section and bridge deck) of 1800 N/m² (a total of 28 kN). The weight of the custom-made bridge deck supports, designed to fit the curvature of the WTB, was also added into the total load.

6.4 Pedestrian bridge: Numerical models

As a first step in the development of the numerical model of the pedestrian bridge, a model representing the blade girder only was carried out. A SolidWorks file of the blade obtained from the blade manufacturer in 2021 was used to create the models in Abaqus. The file was processed in SolidWorks first to export it with a format that can be imported in Abaqus. The file format for import in Abaqus were IGS, STEP and Parasolid (X_T). The file format that gave the best results in terms of quality of the model, need to repair broken/missing parts and compatibility was the IGES format (It was however necessary to work on the imported model in order to be able to use it for a numerical analysis)



5. Blade design

5.3 Sectional properties

The sectional properties of each section illustrated in Figure 5.3 are listed in Table 5.1.

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22

Figure 5.3: Blade sections NWP28.3 ATV

Table 5.1: Sectional blade data NWP28.3 ATV

Section	Radius	Mass [kg/m]	EI_{flap} [MNm^2]	EI_{edge} [MNm^2]
0	0.0	753.6	1310.0	1360.0
1	1.1	286.4	1230.0	1360.0
2	2.1	240.0	863.0	1050.0
3	3.6	240.0	863.0	1050.0
4	4.1	240.0	863.0	1050.0
5	4.6	240.0	863.0	1050.0
6	5.1	216.8	741.0	1050.0
7	6.1	204.8	687.0	1060.0
8	7.1	175.2	406.0	886.0
9	9.1	136.8	219.0	508.0
10	11.1	126.4	127.0	427.0
11	13.1	102.4	68.9	295.0
12	15.1	103.2	30.0	208.0
13	17.1	88.0	22.5	134.0
14	19.1	79.2	16.2	102.0
15	21.1	89.6	9.3	64.4
16	22.1	80.8	6.65	47.3
17	23.1	73.6	4.24	38.2
18	24.1	61.6	2.73	32.0
19	25.1	35.2	1.27	17.1
20	26.1	31.2	0.479	10.2
21	27.1	28.0	0.163	4.85
22	28.1	15.2	0.030	0.97

Figure 28 NWP28.3 ATV WTB internal structure.

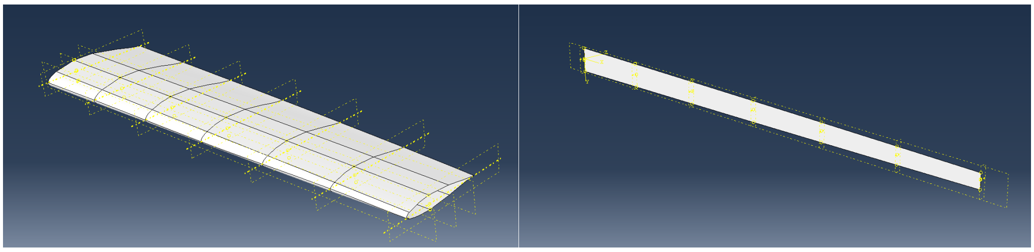


Figure 29 Blade parts, assembly and meshing in FE software Abaqus.

The section of the WTB used as a girder was cut from the full blade model as shown in Figure 28 and Figure 29 above. The blade is made of two parts that are assembled together. The first part is the blade outer shell, divided in section (leading edge, trailing edge and carbon fibre spar cap). The second part is the I beam spar web. The 2 parts are assembled using tie constraints.

The parts are meshed with a total number of nodes of 3969, and 3840 elements (3072 linear quadrilateral elements of type S4 *(Blade outer shell)* and 68 linear quadrilateral elements of type S4R *(Spar)*).

The blade boundary conditions used are such as the blade is simply supported. For the load set-up, the design load (Traffic Class (TC) (1-5): 4) is a combination of the live loads and dead loads:

- Live loads: 2000 N/m2
- Dead loads: Blade weight (varying along the length) + bridge deck mass (1540 N/m)

To simplify the model, all the loads are combined as 1 pressure load on the top surface of the blade (**3800 N/m^2**).

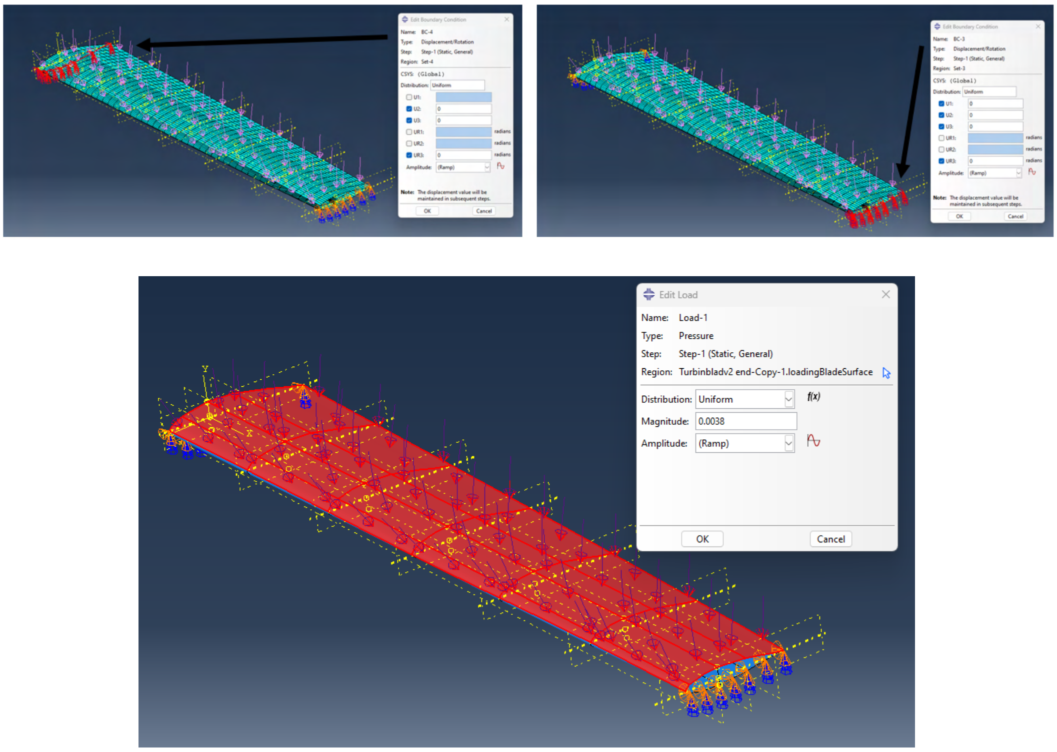


Figure 30 Boundary conditions: Blade simply supported on both ends of the blades. The loading is applied as a pressure on the top of the blade.

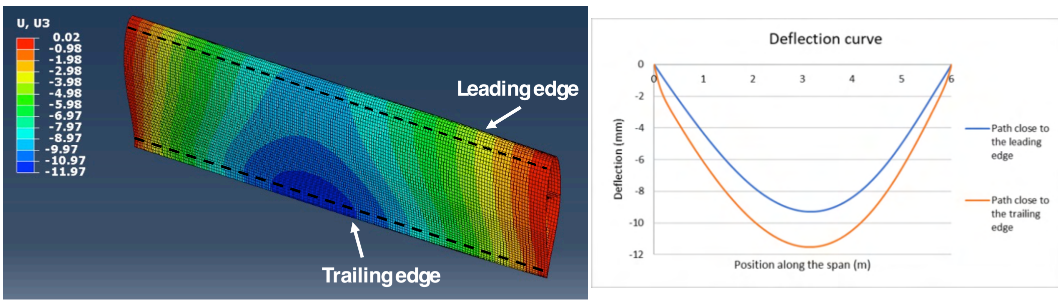


Figure 31 Numerical results: blade deflection.

This diagrams and contour plot in Figure 31 show the final deflection of the blade under a distributed flexural loading of 3800 N/m^2. The 2 curves represent the deflection on the bottom surface of the blade close to the leading edge (blue / top) and close to the trailing edge (red/bottom). The maximum deflection is 11.52 mm at a distance of 3.15 m from the support.

Using the calculation tool developed in the work package 5 of the CIRCUBLADE project (cutting support tool and digital platform for EoL blade management), a similar loading on the same blade section yields a very comparable deflection at a similar position along the blade (see Figure 32). This was used to validate the Abaqus model of the blade developed in this part of the study.

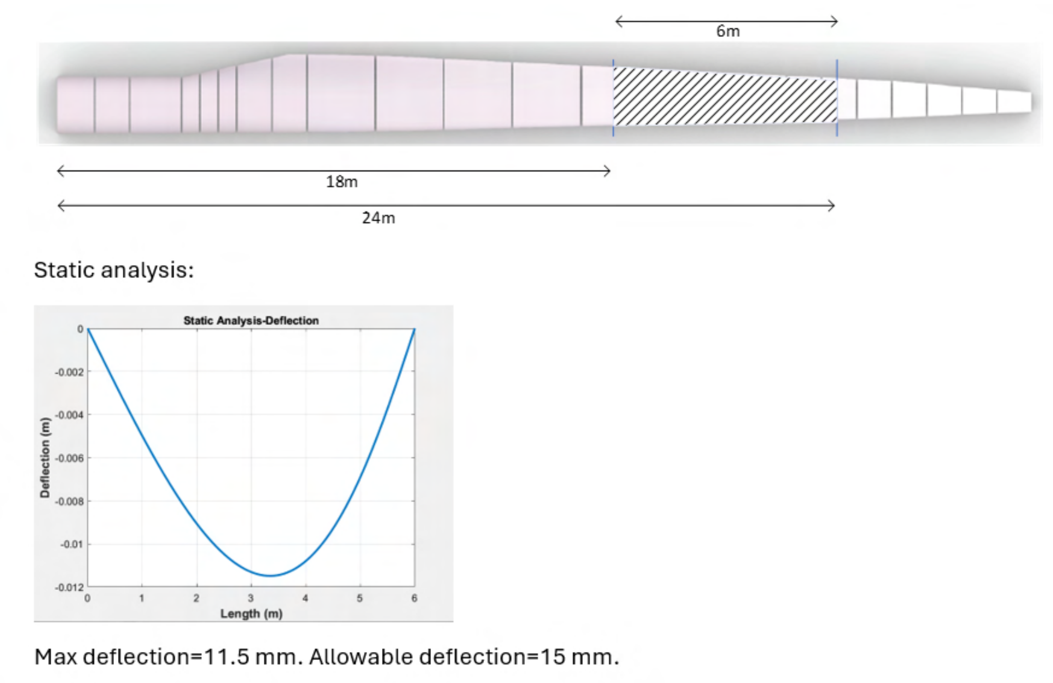


Figure 32 Deflection results of the blade under loading obtained using the calculation tool developed in WP5.

Adding the deck to the numerical model:

The FE model is further developed by adding the deck on top of the blade. The deck used is the decking system developed in the previous project RECINA (André et al., 2024). The deck is a sandwich panel system. It is made of panels from Podcomp (act as skin) and GFRP pipes from Hitachi Energy sliced in 100 mm long cylinders (act as core).

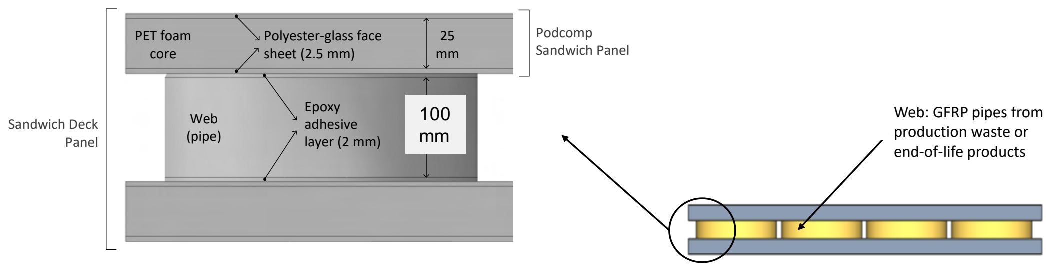


Figure 33 Structure of the panels used for the decking system.

The material model used for the element of the decking system have been simplified. Instead of considering the full orthotropy of the GFRP parts, all materials were assumed to be isotropic with linear-elastic properties. At this stage of the model development, this assumption is considered as sufficient to give indication on the overall behavior of the bridge under loading.

The modulus of elasticity of the constituents is as follows:

- PET foam: 100 MPa,
- Glass fiber-polyester composite face sheets: 12 Gpa
- Webs (i.e. pipes): 38 Gpa

- Epoxy adhesive: 5 GPa.

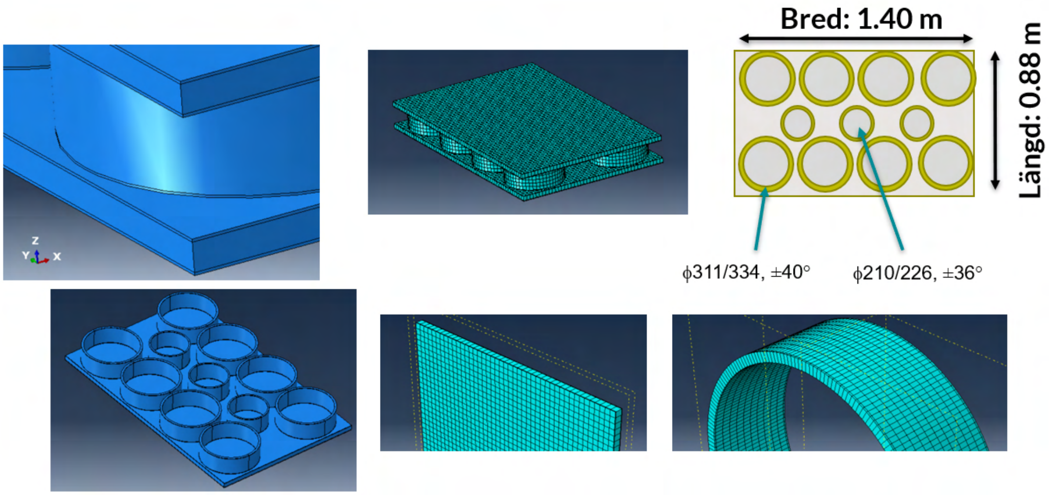


Figure 34 Numerical model for the decking system: geometry and mesh.

The panels and the cylinders are made with solid elements C3D8R. Each skin is made of 9240 elements (PET core and GFRP skin). The small cylinders are 104 mm high (100 mm GFRP cylinder and 2x2 mm adhesive) and are made of 2400 elements. The large cylinders follow the same composition as the small cylinders and are also made of 2400 elements.

Seven (7) custom made supports positioned along the blade were made. These supports are made of GFRP and follow the local curvature of the blade. The width and height of the supports has been chosen to keep enough clearance under the deck and to give enough support to the panels. Possible modification of their geometry is however foreseen to comply with yet unknown manufacturing parameters.

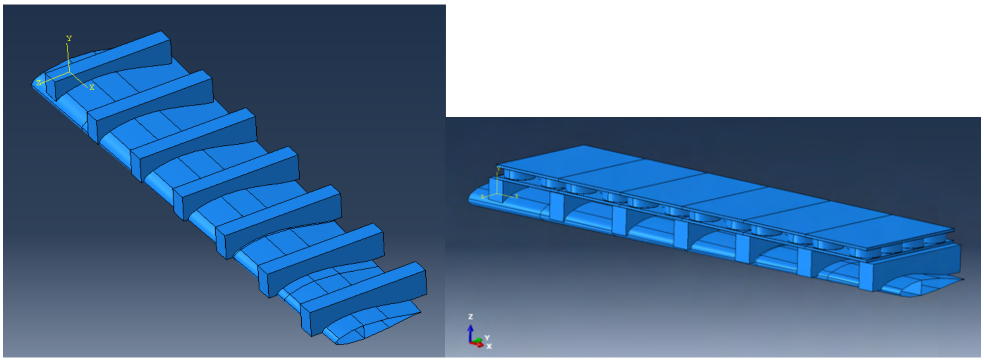


Figure 35 Custom supports for the decking system on top of the WTB girder.

To simplify the model at this stage of development, all surface interactions between the different parts of the models are considered as tie constraints, this means perfectly bonded with no relative displacement between surface pairs during the loading. This may be modified at a later stage.

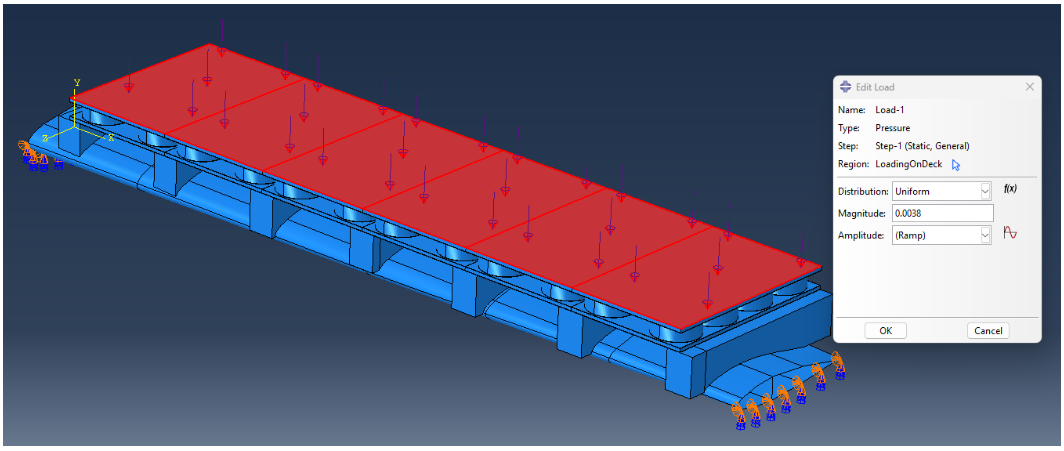


Figure 36 Loading and boundary conditions for the full model (blade, support, deck).

The boundary conditions (BC) were kept the same as for the blade previously loaded without deck. The loading was however modified and moved from the surface of the blade to the top surface of the bridge deck (see Figure 36). The load magnitude is the same, i.e. **3800 N/m^2**.

Results:

In terms of deflection, the maximum allowed at SLS (Serviceability limit State) is L/400 = 6000/400 = 15 mm. The maximum deflection observed (5.06 mm, see Figure 37) is much lower, which means that the deflection fulfils the regulations in terms of SLS.

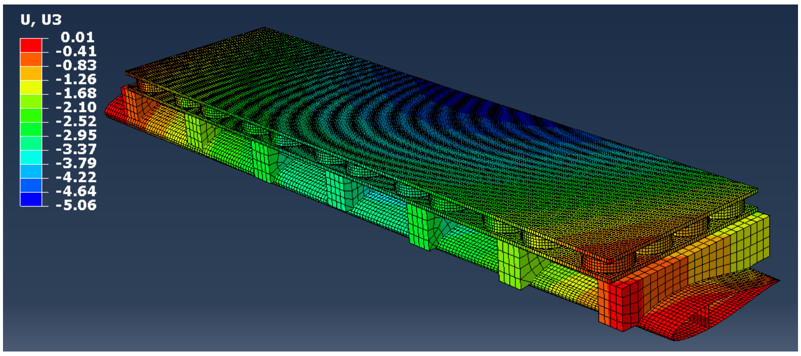


Figure 37 FE model assembly of the pedestrian bridge and contour plot of the deflection under loading (3800 N/m^2).

In this preliminary numerical model, the stress levels observed (from +30 MPa to -30MPa) are moderate in relation to the material strength, which indicates that the risk for damage initiation under this load level is not expected to occur. However, further analysis of local maximum will be necessary to verify that the stresses do not exceed the material strength locally.

In addition to the static analysis, a dynamic analysis was carried out using the calculation tool developed in parallel to the digital platform. The results presented in Table 2 show that requirements in terms of acceleration and frequency are met.

Table 2. Result of the frequency analysis using the cutting tool for the bridge made of WTB section.

Vertical frequencies	**Critical range**
Frequency Mode 1 (Hz) = 7.0	First mode 1.25Hz ≤ f ≤ 2.3Hz
Frequency Mode 2 (Hz) = 28.0	Second mode 2.5Hz ≤ f ≤ 4.6Hz
Horizontal frequencies	
Frequency Mode 1 (Hz) = 18.2	0.5Hz ≤ f ≤ 1.2Hz
Frequency Mode 2 (Hz) = 72.4	

Both vertical and horizontal fundamental frequencies of the bridge are outside the critical range and no issue with the dynamic behavior of the bridges is expected.

7. Manufacturing and mechanical testing of prototype for the pedestrian bridge concept

7.1 Manufacturing

For the manufacturing and assembly of the pedestrian bridge prototype, the focus was placed on two key solutions: (i) enabling easy disassembly of components to facilitate material separation at the bridge's end of life (EoL), and (ii) using similar types of materials for assembly to simplify waste management when the bridge reaches EoL.

A prototype has been created to demonstrate how the deck can be connected to the blade using bolts, bushings, steel plates, and rubber plugs (see Figure 38). This design enables easy disassembly at the bridge's end of life, aligning with circular design principles.

The prototype is a great basis to further develop the design and manufacturing of longer span bridge blade. Some adhesive and PU sealant will be used to strengthen and seal the connection support/blade and support/panel. The use of an adhesive film was also discussed as an alternative solution. The rubber plug and steel plate were completed with a sealant material to close the gap between the steel plate and the blade, and to prevent water to enter the blade through the bolt hole.

Figure 38 Concept: prototype for the assembly of the deck on the WTB and of the handrailing supports.

Another assembly option is adhesive bonding, which is a promising solution when the process can be carried out in a controlled environment to prevent surface contamination. However, it is important to note that there are limitations related to the final size or length of the assembled bridge, particularly regarding transportation to the installation site. In the case of the project bridge prototype, the total length is under 7 meters, which eliminates any transportation concerns. Therefore, we opted for adhesive bonding for the prototype's assembly since (i) the bridge could be assembled indoors in a controlled environment, and (ii) its short span and size allowed it to be transported via a standard truck (less than 12 meters).

As mentioned earlier, the blade section used as a girder for this prototype was recovered from an ATV blade and transported to Composite Design's facility in Arlöv, Sweden (see Figure 20). One of the end sections, where the cutting was done, remains open but will be sealed during the final finishing stages of the bridge prototype (see Figure 39). The sealing may provide additional strength at the support area, which would enhance the mechanical performance of the bridge.

Figure 39 WTB section – end part where the cutting was done.

The bridge prototype consists of four main components: (1) the deck, (2) the supports placed between the deck and the blade, (3) the blade section serving as the bridge girder, and (4) the two supports on which the entire bridge rests. Due to the varying curvature of the blade surface along its length, custom-made supports were fabricated to fit the contour of the blade. Similarly, custom supports were created for two main ground supports of the bridge. Adhesive was used to assemble all the components. An Isophthalic (ISO) polyester adhesive was applied for the joints on the blade surface, while a PL400 construction adhesive was used to bond the deck panel to the deck supports.

Figure 40 Assembly of the bridge deck supports on the blade using adhesive bonding.

Figure 41 Assembly of the deck on the deck supports.

Figure 42 Bridge ground support (here on a scale used to monitor the load during the mechanical testing).

7.2 Mechanical testing

The prototype of the pedestrian bridge has been tested in bending in order to verify the stiffness of the bridge (comparison with FE models) and the performance of the connectors.

From the FE models, we observed that under a Serviceability Limit State (SLS - live load of 2000 N/m^2), the bridge shows a mid-span deflection of approximately 5 mm. The bridge was physically tested at this SLS load level in bending using four water containers as the load application method. Each container holds up to 1000 liters, equating to a total load of 40 kN when fully filled. Deflection was measured at mid-span (L/2) with a digital dial at the trailing edge (TE) and a laser dial at the leading edge (LE). Additionally, deflection at L/4 from each support was recorded using 2 digital dials at the TE and 2 analog dials at the LE. In total, five dial gauges and one laser measurement device were employed. To monitor the applied load, load cells were placed at the supports, allowing us to capture both the load and deflection over time and plot the load-deflection curve. The entire test was video recorded for further analysis and to investigate any unexpected events during the loading process.

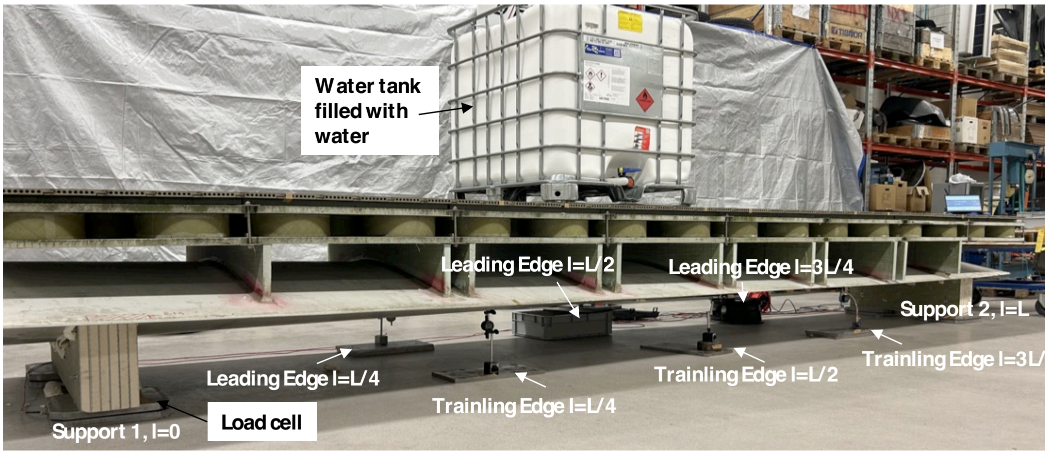


Figure 43 Position of the deflection measurement devices, load cells and load (water tank) during the test.

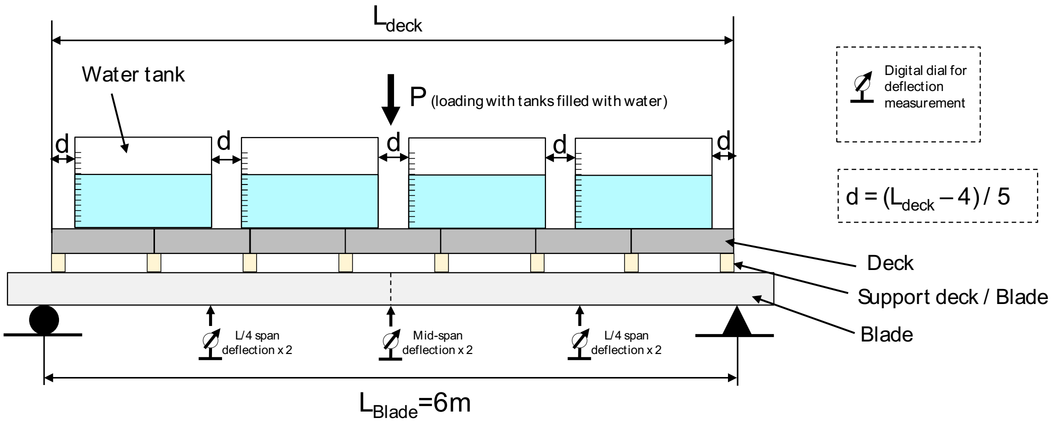


Figure 44 Test set-up.

During the loading of the bridge, the load was gradually increased by adding pre-filled water tanks. Each tank had a total weight of 350 kg, corresponding to an approximate load of 3.39 kN. The loading sequence was as follows:

- A: 1 water tank placed at mid-span, total load 3.39 kN.
- B: 2 water tanks placed on either side of mid-span, total load 6.78 kN.
- C: 3 water tanks evenly distributed along the span, total load 10.20 kN.
- D: 4 water tanks evenly distributed along the span, total load 13.94 kN.
- E: 4 water tanks evenly distributed along the span, with an additional 1 kN of water, total load 14.92 kN.
- F: 4 water tanks evenly distributed along the span, with another 1 kN of water, total load 15.90 kN.
- G: 4 water tanks evenly distributed along the span, with extra weight added by having two people stand on the bridge, total load 17.49 kN.

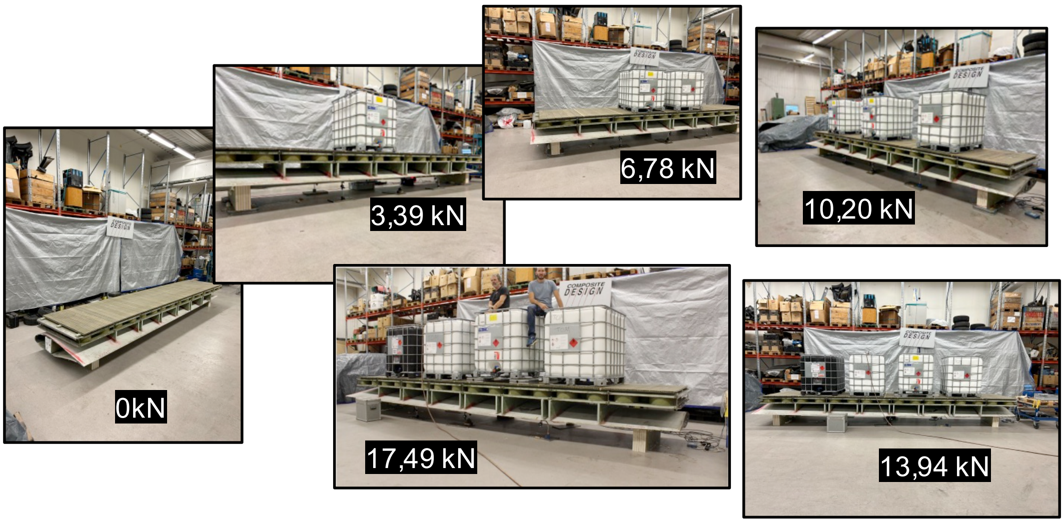


Figure 45 Bridge loading sequence and load magnitude.

The load-displacement curves at mid-span and along the span are shown in the figures below. As expected, due to the asymmetric structure of the blade between the trailing edge (TE) and the leading edge (LE) — with the LE being stiffer — the deflection at the TE is greater than at the LE. The maximum global deflection at 17.49 kN is approximately 7 mm, which is well within the acceptable limit of L/400 (6000/400 = 15 mm). The finite element (FE) model results showed a stiffer response, which was anticipated due to the approximations made for the connectors (tied constraints). In reality, some local elastic deformations occur in the connector areas of the adhesive joints during loading.

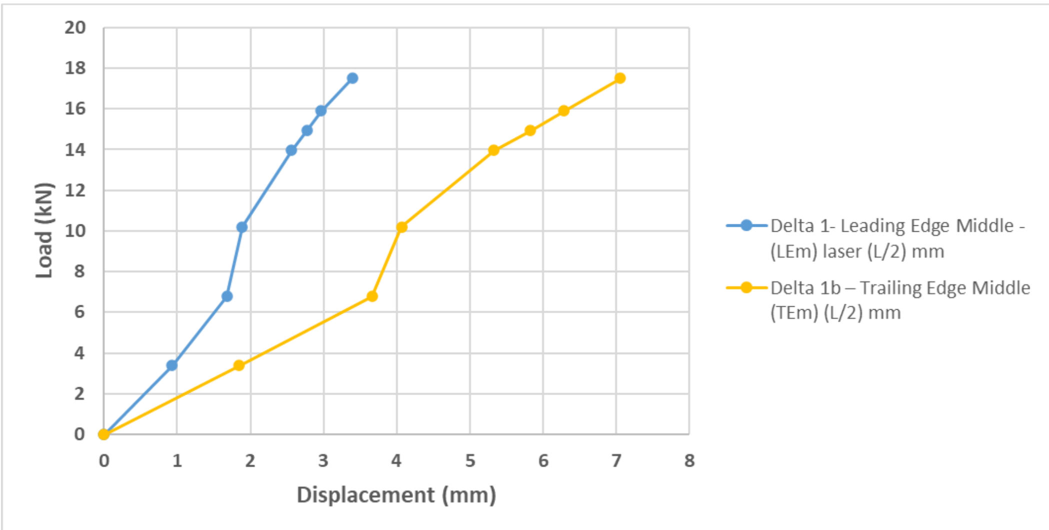


Figure 46 Load vs displacement curve at mid span (leading edge and trailing edge).

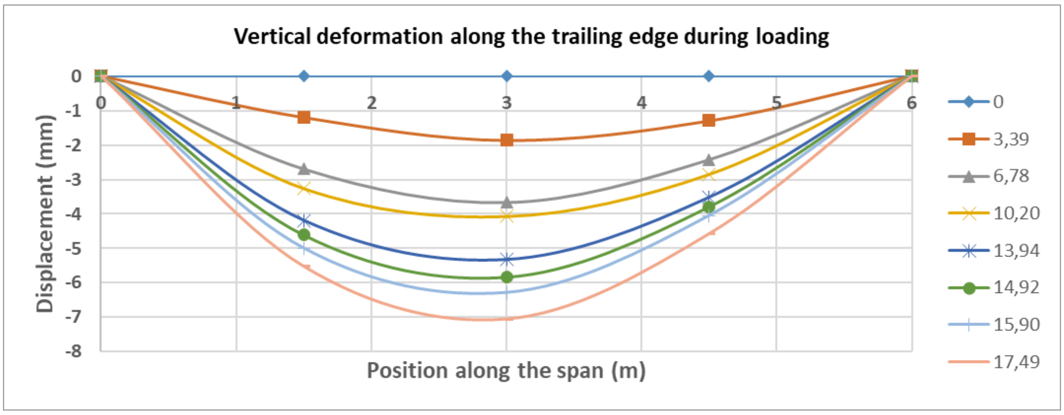


Figure 47 Vertical displacement along the span during loading – Trailing edge.

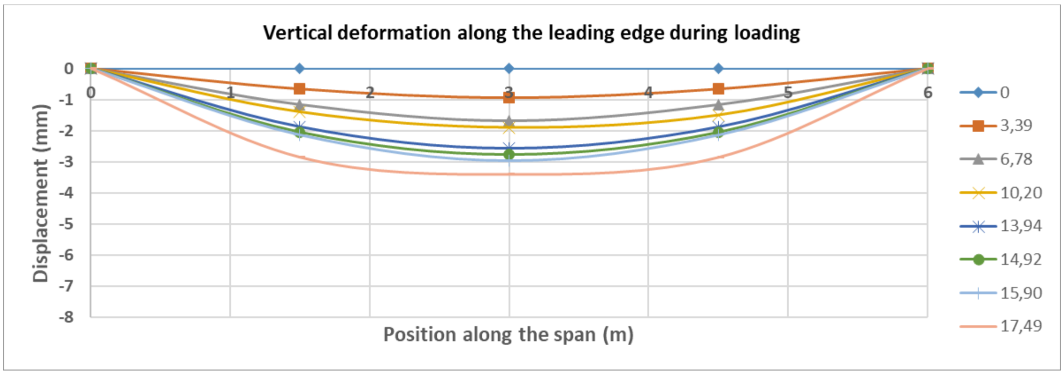


Figure 48 Vertical displacement along the span during loading – Leading edge.

8. Development of the digital platform to facilitate the circular management of EoL WTB

A key factor in building a strong value chain for end-of-life (EoL) wind turbine blades (WTBs) is obtaining detailed information on the type, availability, location, and condition of the blades. This data must be accessible early enough to enable proper planning for all stakeholders. Historically, sharing WTB data has been limited due to industrial intellectual property protections. In 2023, the first steps towards standardizing data exchange were made with the introduction of the "Blade Material Passport" across various WTB manufacturers (Deombldes, n.d.). However, greater collaboration between manufacturers and operators is needed to fully realize the potential for repurposing EoL WTBs.

The Vindbrukskollen website (Länsstyrelserna, n.d.) is Sweden's most comprehensive open-access database, listing over 5,000 wind turbines with details such as location, turbine type, construction year, and owner. Yet, other critical information for managing EoL WTBs, like decommissioning schedules and repair history, still requires direct communication with turbine owners.

As part of the Circublade project, a digital platform was further developed from (André, 2023) to incorporate essential features such as user interface filters, cutting tools, secure login, access requests, and a routing tool to streamline logistics. The platform’s cutting tool is designed to optimize the decommissioning process by ensuring WTBs are cut precisely, reducing transport costs and ensuring the final repurposed product, such as a bridge, meets structural design standards.

Using the data from the Swedish wind parks database Vindbrukskollen (Länsstyrelserna, n.d.), an inventory and analysis of existing wind turbines (WTs) in Sweden was conducted. The study indicates that approximately 15,000 wind turbine blades (WTBs) will reach end-of-service (EoL) status within the next 20 years. Since various types of WTs are installed across Sweden, the WTBs also vary in structure and material composition, which is a crucial factor to consider when planning their repurposing.

One fourth of the WTBs reaching EoL between 2020 and 2030 will be from Vestas V90 turbines. This presents an opportunity to develop specialized waste management strategies for this specific WTB type, potentially improving the efficiency and cost-effectiveness of the process. Additionally, WTB waste generation is expected to be unevenly distributed across Sweden. The southwest region is likely to produce the most waste until 2030, while the northern regions are anticipated to see higher waste volumes in later years (Figure 49).

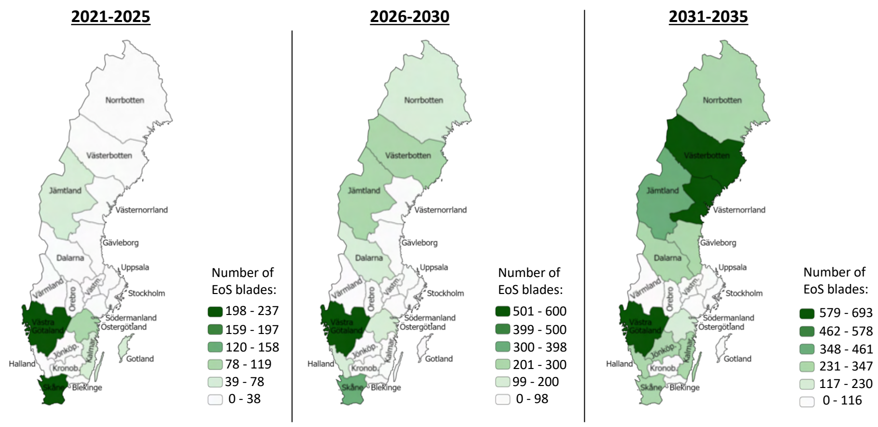


Figure 49 Mapping EoL WTBs in Sweden from the estimated decommission year.

Currently, most municipalities have digitized the permitting process, and digital design along with Building Information Modeling (BIM) are commonly used in construction projects. These technologies can converge on a digital platform to create an effective framework. Such platforms also serve as hubs that streamline and speed up collaboration among various stakeholders in the value chain, including wind turbine operators, WTB owners, decommissioning companies, repurposing specialists, and logistics firms. For example, a digital platform can facilitate material exchanges and lower transportation costs. Online marketplaces focused on building materials can allow contractors, architects, and designers to source materials from existing structures, supporting the circular economy and reducing the need for new resources.

Figure 50 shows the logical workflow of the digital platform created for the CIRCUBLADE project. This platform serves two main purposes: (i) to accurately estimate the quantity of various WTB waste streams across different wind turbine types, and (ii) to offer optimal management strategies for these waste streams based on economic and environmental considerations.

Key features of the platform include: (1) user identification and addressing needs at various stages of the value chain, (2) secure access to WTB data within the databases, (3) advanced search and filtering options, (4) tools to connect suppliers with buyers and (5) sustainable transport solutions.

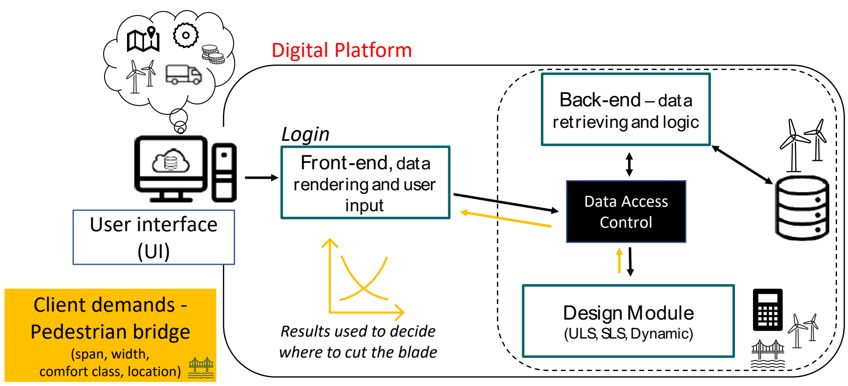


Figure 50 Digital platform: logical workflow.

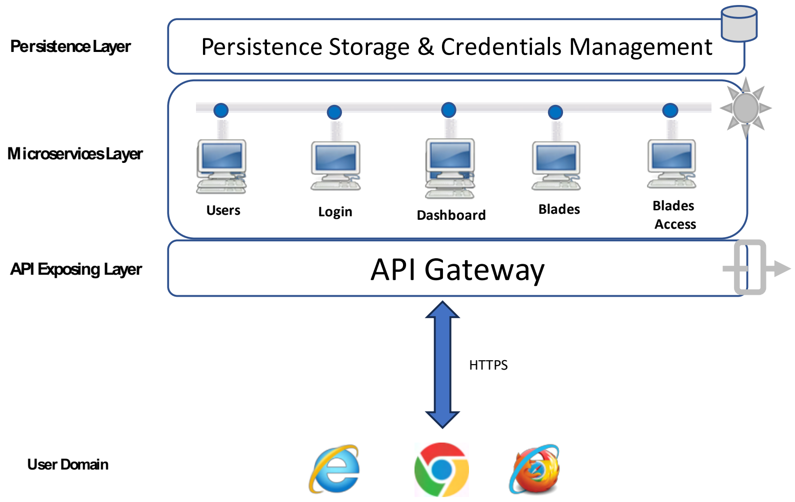


Figure 51 Digital platform architecture: layered model.

The digital platform architecture (Figure 51) follows a layered approach, with functional requirements implemented as microservices. The architecture consists of three main layers: (i) the Persistent Layer, which stores user data, login information, and details about WTBs; (ii) the Microservices Layer, which handles data processing and manages WTB-related information, including secure sharing functionalities; and (iii) the API (Application Programming Interface) Gateway Layer, which presents all microservices to end users in an organized manner.

To improve user interaction with the microservices, a user experience (UX)-focused dashboard has been developed. This dashboard acts as a user-friendly interface, offering features like user registration, authentication, authorization for data sharing, and the management of data exposed by various microservices. The user-centric design is intended to make the platform intuitive and efficient, allowing users to easily navigate and utilize the microservices in a secure manner.

The WTB cutting software created in this project is a finite element-based structural analysis tool designed to facilitate the precise cutting of WTBs on-site for use in pedestrian bridge construction. This software thoroughly analyzes the structural properties of a bridge using a WTB as the main load-bearing component, customized to the user's specified length and dimensions. It includes three primary types of analysis: frequency analysis, dynamic analysis, and static analysis.

9. Conclusions

The goal of our project was to investigate a potential circular economy solution for reusing large quantities of EoL wind turbine blades.

Understanding how municipalities and the public view new, innovative infrastructure and architectural products, is a crucial step in enabling the future integration of products made from EoL wind turbine blades in urban infrastructure. The municipalities that were involved in our study showed an interest in the idea and were willing to test new applications. However, they stated that it is vital to ensure that these new applications meet the same standards and requirements as those made from conventional materials. Furthermore, even if the interest was there, when it came to taking concrete actions to apply the solution developed in the project, the internal decision-making process at the municipalities were a hinder. One of the challenges concerned financial resources for the installation of the bridge, as well as internal communication between departments within the municipality. Understanding the technical aspects of applications such as a bridge made of unconventional material was another hinder that was identified. Another aspect is the concept proposed in the project. A bridge is an advanced and complex product that must fulfill complex standards and certifications. It might have been better to propose a simpler product as the first application.

Collaboration with constructions companies is important to promote and build more applications made of EoL wind turbine blades. As well as making sure that the application meets relevant standards. Therefore, there is a need to spread the knowledge about the materials from EoL wind turbine blades via the sustainability guide developed in the project. The guide is intended to be shared with municipalities and other actors with the purpose of raising awareness about the potential of using repurposed wind turbine blades.

In the project the logistics of repurposing EoL WTB as analyzed. The results showed that the machinery and transportation of repurposed wind turbine blades play a significant role in the overall cost of repurposing projects. With transportation costs on the rise, sometimes accounting for up to 30% of total project expenses, reducing these costs is crucial for keeping projects affordable. As end-of-life wind turbine blades become more common, the logistical system must be improved, as emphasized by experts during interviews. Centralizing production could boost efficiency, but large-scale viability depends on the efficient transport of wind turbine blades across EU borders. Currently, decommissioned blades are classified as waste, requiring time-consuming permit processes for transport.

One possible solution is to reclassify wind turbine blades (WTBs) designated for repurposing as products rather than waste, which would help reduce transportation lead times. However, it is important to consider the trade-offs between large-scale processing facilities and more localized production sites. Environmental analysis indicates that transportation is a major contributor to the CO2-equivalent emissions of repurposed WTBs and significantly affects the overall logistics costs.

A digital platform aimed at simplifying the management of end-of-service WTB was further refined in the project. Its purpose is to catalog all WTBs in Sweden, along with the relevant data needed for repurposing after they reach EoL. The platform's design prioritizes data security and safety, ensuring that sensitive information (such as WTB structure, material composition, repair history, and decommissioning year) is protected but still accessible for effective repurposing. WTB data can be retrieved upon request by the blade owner. Additionally, practical tools, such as a cutting and calculation tool and a routing tool, have been incorporated into the platform. The key goal is to reduce the difficulties between the WTB decommissioning and repurposing processes, facilitating the creation of new value chains for WTB reuse. These tools offer features like simplified life cycle cost analysis and a cutting guide with initial structural evaluations (i.e., determining the best cutting section for repurposing).

Transporting waste materials for repurposing generates emissions. The LCA performed in the project helps quantify the environmental impact of reusing WTBs, comparing the effects of using recycled versus virgin materials. To promote sustainable and environmentally responsible practices in reusing construction waste, integrating LCA into the platform is a key consideration for future updates.

As a growing number of wind turbines enter the decommissioning phase, there is an urgent need to establish sustainable value chains for managing their components, particularly for WTBs. The CIRCUBLADE project suggests repurposing as a solution, which aims to preserve most of the inherent value of WTBs. Investigations have focused on innovative products made from decommissioned WTBs, such as pedestrian bridges, façade elements, and noise barriers. However, several key challenges remain, including:

- Lack of awareness and knowledge: Many construction companies, builders, and contractors may be unaware of the benefits of reusing WTBs or lack the expertise to implement it effectively.

- Cultural factors: In certain regions or communities, cultural attitudes and perceptions about using recycled or repurposed materials may hinder the adoption of WTB reuse.

- Quality concerns: Concerns over the quality of end-of-life WTB materials, including potential contamination, may limit their use in certain applications.

- Regulatory barriers: Existing regulatory frameworks and policies do not sufficiently support the repurposing of WTBs, making it difficult to obtain necessary permits and approvals.

- Logistics and transportation: Moving large quantities of WTBs can be logistically complex, posing challenges for transporting materials to repurposing facilities.

- Economic factors: The high costs associated with transporting, sorting, and processing end-of-life WTBs can make repurposing less economically viable compared to using virgin materials.

- Lack of infrastructure: The absence of adequate sorting, processing, and storage facilities makes it difficult to efficiently upcycle decommissioned WTBs.

To reach a circular economy for EoL WTB, these challenges need to be addressed throughout all stages of the value chain. This requires a large-scale transition, including policy changes, the identification of circular business models, technological advancements, and a change in consumer behaviour. Through these efforts the life cycles of materials in the built environment can be used with circularity as a core principle.

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Appendix

Appendix 1 – Questionnaire for municipalities (PDF)

Appendix 2 - Detailed information on the activities and costs of dismantling wind turbine blades for reuse (PDF).

Appendix 3 – Circularity Guidelines

Appendix 4 – Sustainability Guidelines

The questions that were asked:

1. How many pedestrian/bicycle bridges are there in your municipality?

2. How many bridges are planned to be built in the coming years?

3. How many pedestrian/bicycle bridges need repair every year?

4. What is the main reason for repair?

5. What are the maintenance costs associated with bridges each year?

6. What is the biggest challenge with pedestrian/bicycle bridges – planning, projecting, building, operating from the client's perspective?

7. How is a "bridge project" determined - who draws up specifications, all documents, manufactures it, etc.?

8. How do you view the possibility of procuring new (innovative) bridges with a very low CO2 footprint and very low maintenance costs?

9. Could you comment on how you see, both short-term and long-term, the application of such innovative solutions (applications made from end-of-life wind turbine blades) for bridges or other applications in your region? Examples of applications built from used wind turbine blades - on the attached images.

Huvud aktivitiet	Del aktivitet	Utrustning	Tid	Kostnad
Förberedande aktiviteter inför start	Ansökan om nationella tillstånd	Rivningslov/anmälan vid nedmontering av vindkraftverk. Ansökan om transportdispens vid behov Tillstånd eller anmälan om transport av farligt avfall.		
	Ansökan om internationella tillstånd	Transport av avfall mellan länder	3 - 12 månader	
	Planering av logistik			
Demontering / Förberedning	Förbereda område för att minimera miljöpåverkan	Tält och filtermattor Körplattor Partikelinsamling Tillgång till vatten	Varierar	
	Förbereda såg	Specialanpassad anpassad såg för grävmaskin Specialutvecklad bandsåg Diamantsåg för asfaltbeskäring Dieselgenerator för att driva såg	4 timmar (För grävmaskinssåg)	
	Skära bladen från rotorn	Specialanpassad anpassad såg för grävmaskin Specialutvecklad bandsåg Diamantsåg för asfaltbeskäring	5 - 10 minuter (Effektivt skärning)	
	Kapa blad i mindre delar vid behov	Specialanpassad anpassad såg för grävmaskin Specialutvecklad bandsåg Diamantsåg för asfaltbeskäring	5 - 10 minuter (Effektivt skärning)	
	Lyfta små bitar på truck	Gaffeltruck Grävmaskin		
	Lyfta hela blad på truck	80 tonmeter kran	3 - 10 minuter (Vid lyft av ett blad åt taget)	
Transport	Anpassa infrastruktur efter behov			
	Transport av hela blad	Pråmar Flatbed trailer		500€ - 10.000€ (Per blad)
	Transport kapade blad	Walking floor trailer Dumper Containerbil 40 foot, 32 ton truck		
Anläggning för hantering inför vidare transport	Kapa blad i mindre delar vid behov	Specialanpassad anpassad såg för grävmaskin Specialutvecklad bandsåg Diamantsåg för asfaltbeskäring		
Transport	Transport av kapade blad	40 foot, 32 ton truck		
Vidareförädling från blad till produkt	Förädling			
	Tillverkning produkt	Specialanpassade verktyg		
	Avfallshantering			

Circular Design Principles

This document provides an overview of circular design principles, as well as gives examples of how they can be applied on wind turbine blades.

What is circular design?

Circular design is based on the principles of the circular economy that is dedicated to prolonging the lifetime of a product throughout maintenance/repair, reuse, remanufacturing/refurbishing and in the last step recycling so that the value of the product is maintained in the economy and waste generation is minimized. From linear to circular, the focus shifts from value creation to value preservation and from throughput maximization to waste minimization.

In essence, this design approach encourages a fundamental reassessment of the product creation process, forcing designers to embrace sustainability and environmental consideration as their foundational principles.

There are several strategies to consider when designing and developing a circular product. The first strategy, which affects the rest, is to “think in circles”. It is crucial to have a holistic view and take into account all circular strategy options and think in systems around the product rather than about the product itself. The Ellen MacArthur Foundation Butterfly Diagram is a great example of “thinking in circles” and depicts a visual representation of a Circular Economy, as seen in Figure 1.

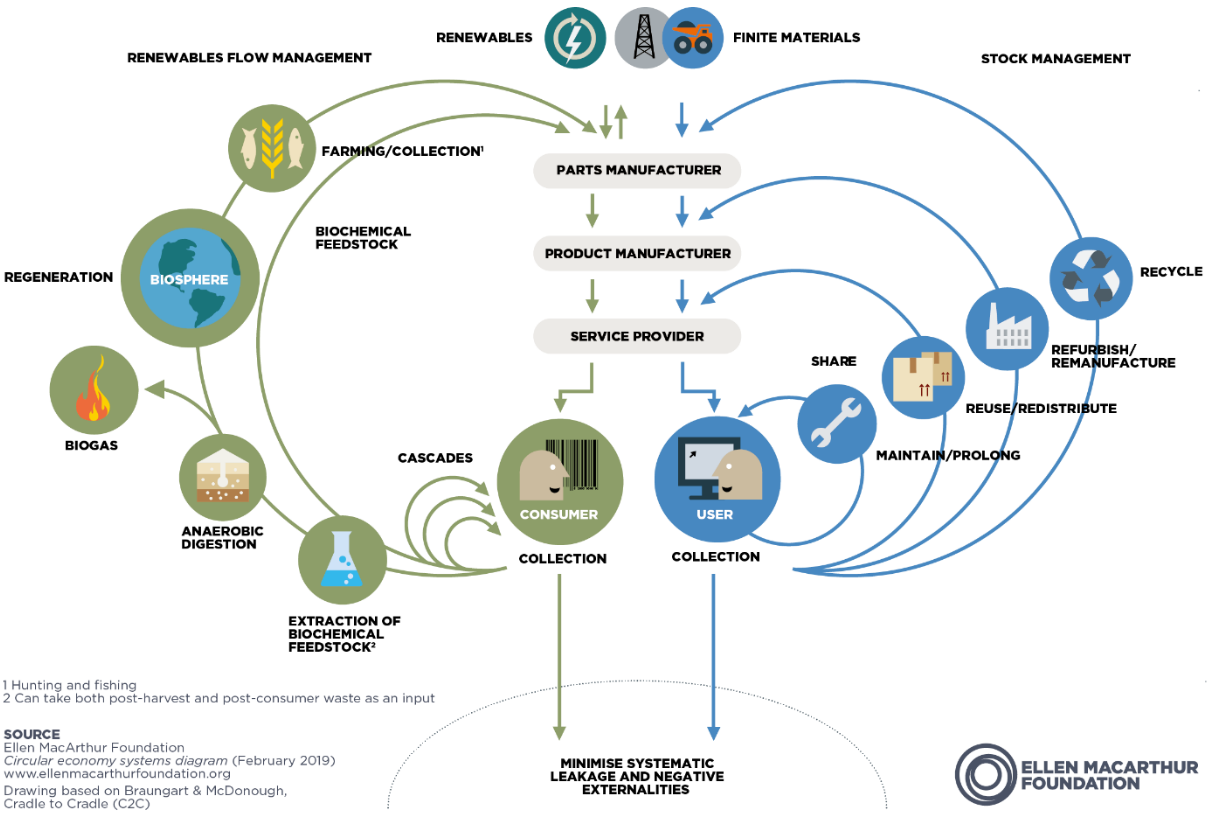

Figure 1 The Butterfly Diagram by the Ellen MacArthur Foundation

The Circublade project was funded by: VINNOVA Sweden's Innovation Agency

Circular design principles

Following the principles of circular economy, actions on maintenance, repair and lifetime extension contribute to extending a product's lifetime.

Six principles underpin closed-loop design, shaping its application across diverse industries. By adopting these six fundamental principles, it is possible to incorporate circular design into a design process, laying the foundation for a future that is more sustainable and resource efficient.

Minimize waste and pollution
A key objective of circular design is to reduce both waste generation and pollution. This objective can be realized by designing products and processes that prioritize efficiency, consume fewer resources, and produce minimal waste over their lifecycle. By diminishing waste and pollution, we can significantly decrease our environmental footprint, fostering a cleaner and healthier planet.

Optimize resources
Circular design promotes the optimization of resource value through the efficient and effective use of materials and energy. This principle necessitates a comprehensive examination of the entire lifecycle of a product or service, encompassing stages from extraction and production to consumption and disposal. The goal is to ensure that resources are employed to their maximum potential, while simultaneously minimizing waste.

Prolong product life
Designing durable, easy-to-maintain, and to repair products is a crucial aspect of circular design. By prolonging the lifespan of products, we reduce the need for frequent replacement, thereby reducing waste generation and preserving valuable resources.

Design for disassembly
To enhance the efficient reuse or recycling of materials, closed-loop design encourages the creation of products that can be easily taken apart. By designing products for disassembly, we enable their components to be repurposed or recycled, further reducing waste and promoting a closed-loop system.

Rethink business models
Crucial for embracing closed-loop design principles are inventive business models that promote circularity, such as for instance product-as-a-service or sharing economy approaches, fostering resource sharing and reducing waste through collaborative consumption.

Encourage collaboration
Facilitating cooperation among diverse stakeholders: designers, manufacturers, suppliers, and consumers, is crucial for formulating and applying circular solutions. Through the exchange of knowledge, pooling resources, and the generation of innovative solutions, we can propel the circular economy forward by nurturing a collaborative environment.

The Circublade project was funded by: VINNOVA Sweden's Innovation Agency

Circular design principles for wind turbine blades

When the design principles described above are applied on wind turbine blades, they can improve the blades' sustainability performance. The principles can be applied both during the design process as well as when the blades have reached their end of life.

Modularity
Design wind turbine blades and other parts of the wind turbine in modular components. This makes it easier for the wind turbine to be easily assembled, disassembled, and replaced. Facilitating maintenance, repair, and upgrades, extending the blades' lifespan.

Material Selection
Prioritize the use of renewable, recyclable, and non-toxic materials in the blade construction. When possible, reduce the number of materials the blades are made of, making them easier to recycle.

Resource Efficiency
Optimize the use of resources such as energy, water, and raw materials in the manufacturing, operation, and decommissioning of wind turbine blades. Implement energy-efficient manufacturing processes.

Circular Economy business models
Consider integrating the wind turbine blades into circular economy models, such as product-as-a-service or leasing arrangements. Maintaining ownership of the blade makes it easier to take care of at the end of life, as well as creating an incentive to keep the blade in service for longer.

Durability and Longevity
Design wind turbine blades to be durable and long-lasting, with a focus on reliability and performance over their entire lifespan. Implement corrosion-resistant coatings and advanced materials to extend operational life and reduce replacements.

Maintenance and repair
Make sure that the most common repairs that must be performed on a wind turbine blade are easily accessible for repairers.

Local Sourcing and Production
Source materials locally and establish local manufacturing facilities when feasible to minimize transportation-related emissions.

Product passport
By including a product passport on the product, it becomes easier to take care of and maintain the blade during its lifetime. A product passport carries information about the blade which can be accessed by the actor taking care of it.

Reuse
Instead of producing new blades, look at reusing old blades that have been decommissioned before the end of their technical lifetime.

Repurposing
When blades reach the end of their technical lifetime as wind turbine blades, they can be used for other applications such as urban furniture or pedestrian bridges. Repurposing the blades reduces the need for virgin materials and utilizes the blades' technologically advanced materials and structures.

By integrating these circular design principles into the development and production of wind turbine blades, it is possible to create more sustainable and resilient energy systems that contribute to a circular economy and mitigate environmental impacts.

The Circublade project was funded by: VINNOVA Sweden's Innovation Agency

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Circularity and sustainability guide for the resources from end-of-life wind turbine blades

Photo: Fairwind/Vattenfall

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Sveriges innovationsmyndighet

About this guide

This guide has been prepared within the R&D project CIRCUBLADE. The CIRCUBLADE project aims to develop a circular solution through the reuse of end-of-life wind turbine blades in new products with a focus on efficient logistics, design and manufacturing as well as the development of a digital tool that helps achieve a higher circularity and resource efficiency. CIRCUBLADE shall contribute to a more responsible and sustainable use of natural resources by reducing the demand for virgin building materials and increasing the sustainable reuse and upcycling of composite waste from end-of-life wind turbine blades.

This guide is intended to spread knowledge about the advantages of fiberglass composite materials and their potential applications in recycling and to guide municipalities, authorities and companies in the purchase of recycled products made of glass composite materials. By reusing fiberglass composite material from wind turbine blades, resource efficiency increases as primary raw material is replaced by recycled material.

There are nine partners collaborating in the project:

The project ran between September 2022 and October 2024

Content

Importance of circularity

The impact from the extraction and consumption of raw materials, as well as the generation of waste causes a large burden on society[1]. Therefore, it is critical to apply strategies that minimize waste flows and use our raw materials in a resource-efficient manner.

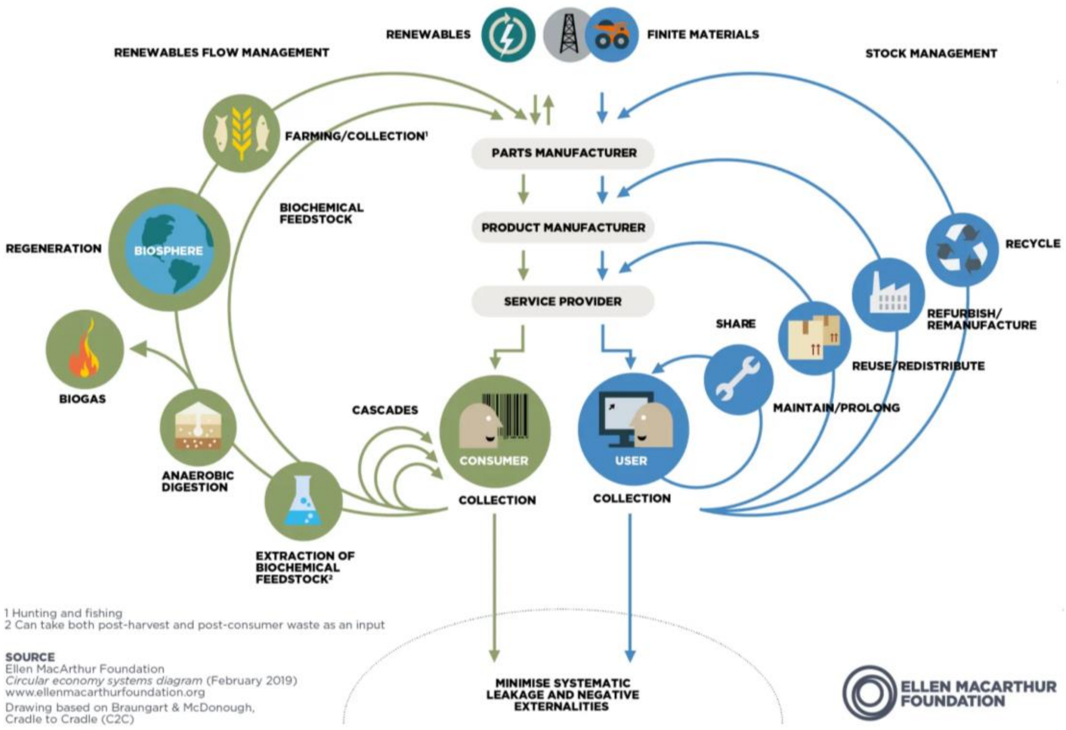
A circular economy means taking advantage of available resources throughout the life cycle through remanufacturing, repair and recycling. It means maximizing the use of materials, energy and water, while minimizing waste, pollution and energy consumption, and contributes to increased resource efficiency.

The butterfly diagram

The figure to the right presents so-called butterfly diagram[2], which shows how circular economy can look like with closed loops of resources.

In the closed system, materials are reused or recycled instead of being discarded after use. This means changing from the traditional linear model (take-make-dispose) to a circular model that promotes continuous use of material. Circular principles have the potential to reduce the need for new raw materials which can mean a reduced burden on the environment and society in the supply chain while reducing waste generation and the need for landfill.

Circular economy is based on cooperation and innovation. All actors in society have a role to play. A decisive role in enabling a circular economy is played by the actors who design new products, new business models as well as technology and processes for handling materials. If leading actors cooperate with the governing bodies and apply circular principles, the impact on society and nature can be reduced.



[1] https://overshoot.footprintnetwork.org/about-earth-overshoot-day/

[2] https://www.ellenmacarthurfoundation.org/circular-economy-diagram

The potential of reusing wind turbine blades

The lifespan of a wind turbine, whose blades are mainly made of glass fiber reinforced polymer (GFRP) composite, is 20–25 years. This means that a large number of turbines will be decommissioned in the near future. In 2025, approximately 36,000 blades are expected to be decommissioned in Europe, which corresponds to 240,000 tonnes of polymer composite waste[3]. Currently, there is no large-scale sustainable and efficient solution to recycle these blades, as thermoplastic composites are complex and expensive to recycle. Small-scale mechanical recycling is becoming more common but it is likely that the majority is used as fuel in cement production, incinerated (to produce heat and electricity) or landfilled. Where the last two mentioned are associated with poor resource utilization and to some extent harmful effects on the environment.

CIRCUBLADE as a project aims to prove that it is possible and there is great potential to extend the life of used wind turbine blades up to 80 years by giving the blades a second life in new innovative applications. An example of this is the use of end-of-life blades in pedestrian and bicycle bridges. The first bridge in the world that has been built from wind turbine blades is in Poland and was built by Anmet, project partner in CIRCUBLADE. Other innovative applications of end-of-life wind turbine blades are playgrounds, benches and noise barriers. There are also more examples, and the possibilities for creative use are great.

Photo: Vattenfall

This guide has been prepared to illustrate the opportunities available to society in the reuse of end-of-life wind turbine blades.

[3] https://iopscience.iop.org/article/10.1088/1757-899X/942/1/012015/pdf

Wind turbine blade and its material

Wind turbines usually have 3 blades that are set in motion by the wind. The rotation that is created generates electricity via a generator that is located at the top of the wind turbine.

Photo: Vattenfall

In a modern wind turbine, the blades are made of several parts glued together. The composition of materials varies from one manufacturer to another, but the most common are polymeric fiber composite materials, which on average represent 85–90% of the weight of a wind turbine blade.

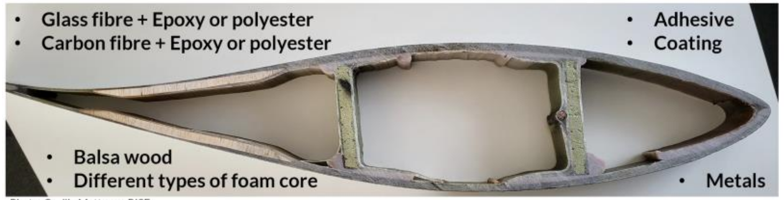


Photo: Cecilia Mattsson, RISE

The problems related to the handling of end-of-life wind turbine blades are above all related to the breakdown of thermoplastics, which make it difficult to separate the material of the blades. Dismounted wind turbine blades are often a high-performance structure that is very durable even after they are taken out of electricity production. This opens up a great reuse potential. In this way, the lifetime of the composite material can be extended and incineration or landfill can be avoided.

Light weight: FRP is light and strong, which allows wind turbine blades to be large and strong. This is critical to enable the efficiency and performance of wind turbines.

Strength and Durability: FRP can be engineered to be very strong and withstand high loads and wind pressure, which is important for blades to function in a variety of weather conditions.

Corrosion resistance: FRP is resistant to corrosion and rust. Wind turbines are often placed in areas where they can be exposed to moisture and extreme weather conditions, and corrosion resistance is a requirement to be able to ensure optimized electricity production and reduce operational interruptions due to for example repair.

Design and malleability: By using FRP, complex shapes and designs can be created, which make it possible to optimize aerodynamics and thus increase energy extraction from the wind.

Longer life and lower maintenance costs: FRP often has a long life and requires less maintenance compared to traditional materials. This reduces the cost of blade repairs and replacement (OPEX).

A simplified life cycle of a wind turbine blade with a focus on disassembly

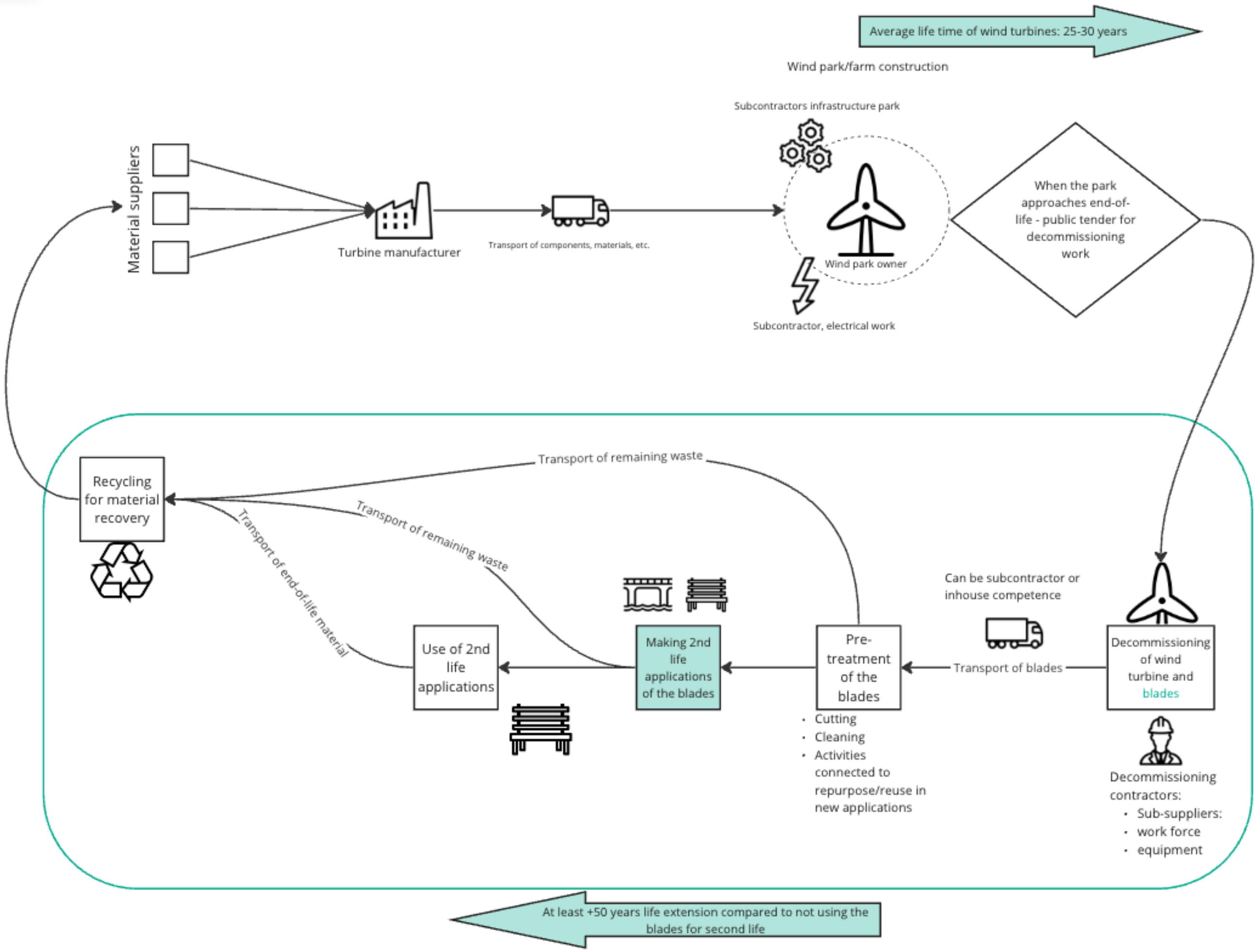
A wind turbine blade is manufactured and assembled to produce electricity for 25 years.

When a wind farm/park is to be dismantled and the blades no longer fulfill their function, the park's owner organizes a procurement for dismantling and decommissioning. Contractor who receives the assignment organizes work force and equipment.

When the wind farm is dismantled, it is possible to reuse the park's blades. To keep a whole blade, specific lifting cranes may be needed to avoid damaging the blade. It is important to have information on how the blade should be transported and cut if applicable. Today there are actors who handle the blades in a way that enables reuse.

In the next step, the wind turbine blades are transported with a truck for further handling – size reduction, polishing, as well as activities linked to the reuse of the blades in new applications. The material that cannot be reused (residues from manufacturing) is transported to material recycling.

By using the material in new applications, the lifespan of the blade can be extended by +50 years. When the new application has reached the end of its life, it is sent for material recycling.

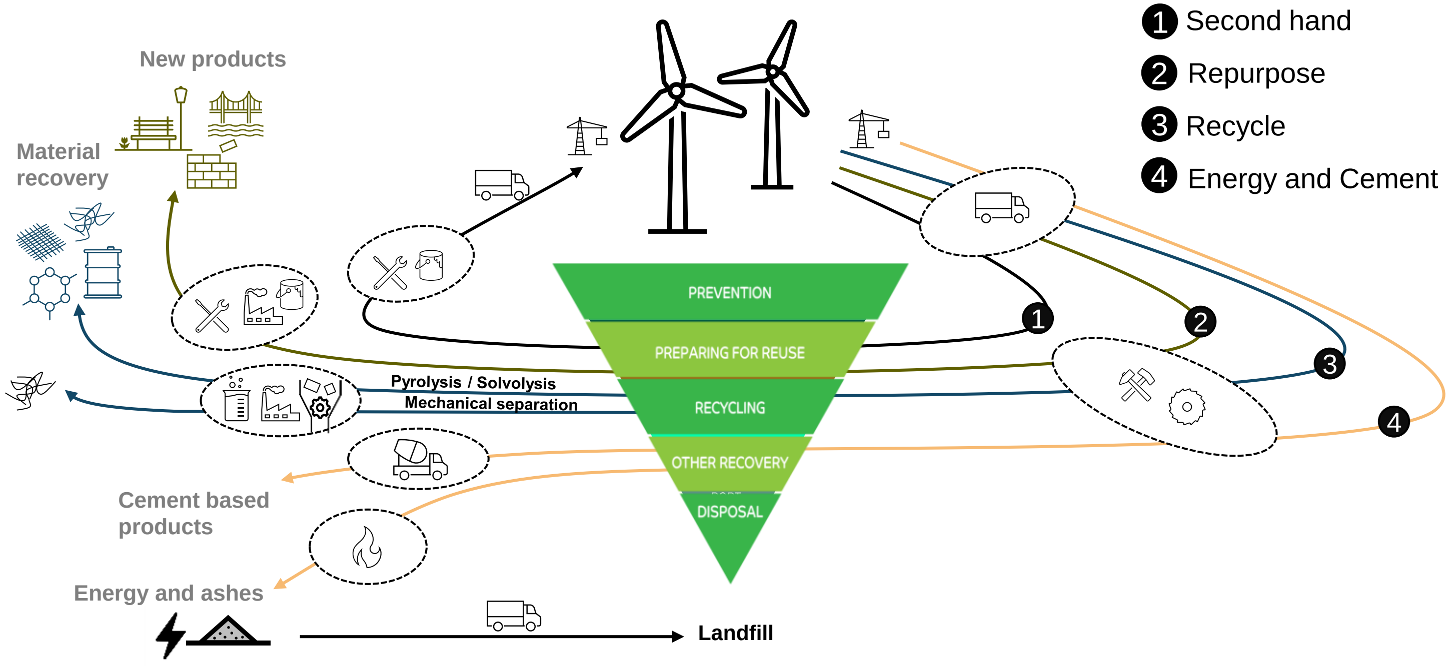


Handling of end-of-life wind turbine blades

The picture to the right shows different processes for handling end-of-life wind turbine blades that exist today and how they relate to the waste hierarchy.

The first natural choice is to extend the life of the product. For a blade in a wind turbine, this involves repairing damages, extending the permit, dismantling the wind turbine for re-installation at a new location, or refurbishing blades and keeping them as a spare part. When this is not possible, reuse of the blade structure in other applications becomes the next process step in the waste hierarchy.

There are already today examples of products and prototypes built with end-of-life blades or parts of these blades - see the next pages of the guide. Design concepts have also been developed for everything from noise barriers and facade elements in buildings to poles for high-voltage lines.



Disassembly	Chemical and mechanical separation
Transport	Incineration
Pre-treatment (cutting, sawing, etc.)	Cement manufacturing
Post-treatment	Energy recovery
Mechanical process	Landfill / Ashes

Reuse possibilities for end-of-life wind turbine blades

Photo: DSV/Vattenfall
The picture shows when DSV dismantles and transports end-of-life wind turbine blades

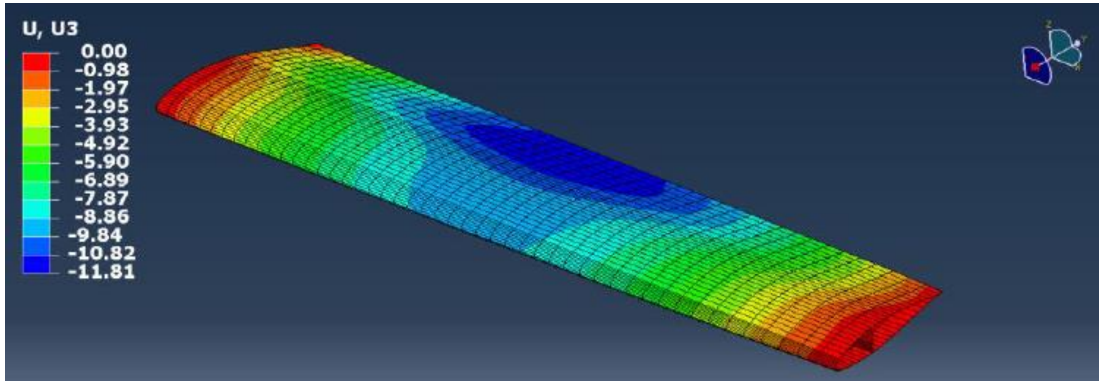
Reuse of wind turbine blades

Reuse of wind turbine blades has several advantages, both economic and environmental. However, it is important to remember that processes that are chosen today are often related to the global context, i.a. whether there are existing and functioning value chains and what volumes can be absorbed in these value chains.

Reuse of wind turbine blades in new products is relatively new. The number of end-of-life wind turbine blades has been constantly increasing since the 2000's, and forecasts show an exponential increase in Europe. Today's quantities are already large and there is an urgent need to find sustainable solutions to manage the composite waste from the wind power industry. At a time when global resource use is striving to reduce the use of virgin materials due to increased costs and reduced material availability, the idea of reusing these strong and durable structures is very relevant. Converting used wind turbine blades into resources for other purposes thus becomes an important strategy for reducing waste and maximizing the value of the existing materials.

Photo: https://www.anmet.com.pl/architecture-made-from-wind-blades/engineering-products/footbridges-and-bridges/?lang=en

An important part of the reuse process is the technical validation of the structure for its new purpose. It includes checking what residual mechanical properties the structure has after its life as a wind turbine blade. This can be an analysis of what damage and repairs are present, visual inspection, analysis of maintenance information if available, possibly deeper lab analysis with advanced tools or testing machines, as well as verifying that the reuse of end-of-life blades in the new application area complies with specific standards and regulations.



The image has been created by RISE in the CIRCUBLADE project. It shows a strength model of a wind turbine blade.

Pedestrian/bicycle bridge – Szprotawa, Poland

First example is a bridge which is the most complex engineering application built from composite materials from end-of-life wind turbine blades.

Pictures present the world's first pedestrian and bicycle bridge built from composite materials from end-of-life wind turbine blades by Anmet (who is a project partner in the CIRCUBLADE project) located in a city of Szprotawa in Poland.

The bridge is the result of three years of work with research and development to ensure that it is possible and safe. The research took place in collaboration with Rzeszów University of Technology.

More information about the bridge can be found here: https://www.anmet.com.pl/architecture-made-from-wind-blades/engineering-products/footbridges-and-bridges/?lang=en

Photo: https://www.anmet.com.pl/architecture-made-from-wind-blades/engineering-products/footbridges-and-bridges/?lang=en

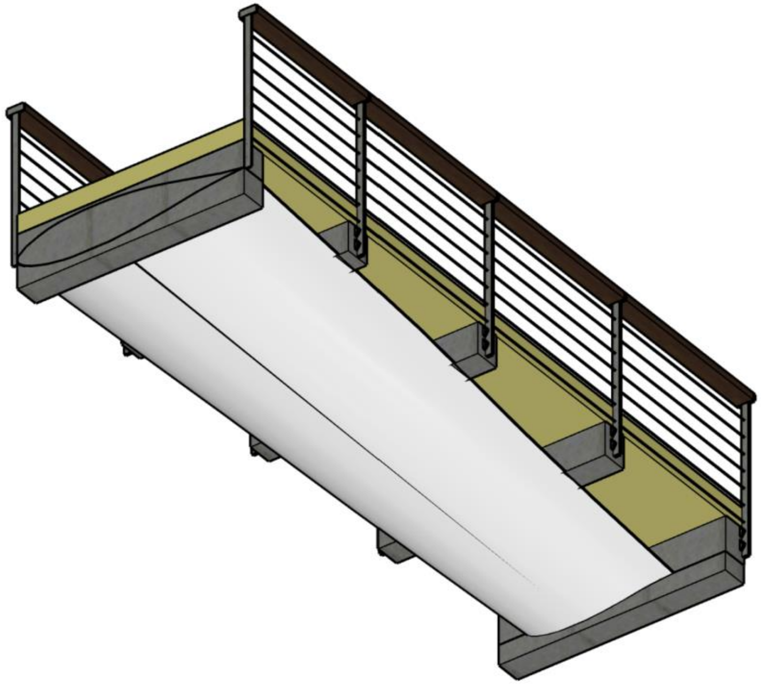
Pedestrian/bicycle bridge made of reused composite material and wind turbine blade

As a part of the research and development project Recina: Reuse of Composite Parts in Infrastructure, which was led by RISE, a pedestrian and bicycle bridge was built from leftover composite materials.

The bridge is designed in a modular way, which enables it to be adapted as needed. In its entirety, the bridge is 7m x 1.3m.

Within the CIRCUBLADE project, the bridge has been updated and reinforced with a blade from a wind turbine, to ensure the bridge's strength and show the possibilities for reuse.

The picture shows the bridge that was built in Recina project and was later upgraded in the CIRCUBLADE project.



The image is created by RISE in the CIRCUBLADE project. It shows how the bridge upgraded with a wind turbine blade will look like.

The use of wind turbine blades as a facade material

In the municipality of Lund, a parking garage will be built where part of the facade material will be from end-of-life wind turbine blades.

The archtecture bureau that designed the project, Lloyds Architects, had a collaboration with part of the CIRCUBLADE consortium and with their help developed the concept.

It is a three meter long part of the blades that will be used for the facade.

The blades have no load-bearing function and are purely for aesthetic reasons. Which shows the breadth of applications for end-of-life wind turbine blades.

For more information go to Lloyds Architects: https://lloyds.se/2024/02/05/pressrelease-fran-vattenfall-om-parkeringshuset-niels-bohr-som-lloyds-har-ritat/

The photo comes from Lloyds Architects and shows the parking garage Niels Bohr. Photo: https://lloyds.se/2024/02/05/pressrelease-fran-vattenfall-om-parkeringshuset-niels-bohr-som-lloyds-har-ritat/

Street furniture and urban solutions - Anmet

Anmet, a project partner in CIRCUBLADE, has developed several different solutions to reuse end-of-life wind turbine blades. They use the blades as the primary part in the products they manufacture, and then update with other materials such as e.g., wood.

The products they create can be used both indoors and outdoors and are creative solutions to what is possible to do with used wind turbine blades.

To read more about Anmet's products, go to:
https://www.anmet.com.pl/architecture-made-from-wind-blades/small-architecture/?lang=en

The photos show different solutions developed by Anmet while reusing end-of-life wind turbine blades. The photos come from:
https://www.anmet.com.pl/architecture-made-from-wind-blades/small-architecture/?lang=en

Noise barrier, playgrounds and other urban infrastructure – Blade Made

The Dutch design and architecture office Superuse Studio has developed a concept called Blade Made.

Within the concept, they have developed proposals for different areas of use for end-of-life wind turbine blades. Among other things, they have developed proposals for noise barriers, which have the potential to be produced on a large scale and use a large part of the volume of end-of-life blades that will be created in the future.

They have built a children's playground made largely of end-of-life blades (picture to the right). They have also built other urban infrastructure from end-of-life wind turbine blades, which shows the variety of products that can be built with the blades.

For more information go to: https://blade-made.com/

The photos come from Blade Made and show concepts how a noise barrier and playgrounds made of end-of-life wind turbine blades might look. The photos come from: https://blade-made.com/portfolio-items/blade-barrier/ och https://blade-made.com/portfolio-items/blade-slide/

Summary and what the reader can do

By manufacturing second life applications, we will extend the life of the blades by +50 years, at which point recycling methods to recycle the blades will exist to a greater extent than they do today.

Some **main messages** from the guide to people responsible for **procurement/purchase** of various infrastructure solutions that are more circular/sustainable are to consider the following:

- Products/applications built from FRP materials require less maintenance compared to products built from conventional materials: wood, concrete, etc. and reduced maintenance needs save time, money and resources for purchasers
- **Have courage to be at the forefront of sustainable development** and **innovation** and the future by choosing (reusing) alternative, robust, sustainable materials that come from end-of-life products (and would otherwise be a waste of resources and pollute the environment due to landfill)
- **The purchasing decisions** can help create demand in the market and encourage further research and development in the area

Photo: Vattenfall

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