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A Holistic and Circular Approach for Managing End-of-Service Wind Turbine Blades

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Abstract: This paper aims to define the challenges and requirements necessary for the holistic management of wind turbine blades at the end of their service (EoS). Conducted within the Swedish research project Circublade, this study focuses on Sweden, although many challenges and findings are applicable to other countries. Various alternatives for managing EoS wind turbine blades exist at different levels of market maturity, but this paper specifically focuses on repurposing the blades into new products. The development of three concept designs—short-span pedestrian bridges, façade elements for building applications, and noise barriers for roads and railways—has been explored, along with aspects related to material sourcing, logistics, and implementation. For material sourcing, a digital platform containing blade data and tools to facilitate repurposing has been developed. An environmental evaluation of the different concepts highlights the significant impact of transportation on the overall environmental footprint, underscoring the necessity of a holistic approach to managing EoS blades.

Keywords: fibre-reinforced polymer; composite; circular economy; waste; repurpose

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1. Introduction

Since the mid-1990s, there has been continuous expansion in wind farm construction in Europe and North America. This growth has mostly occurred without thoroughly considering and planning the management of wind turbines when they reach their End-of-Service (EoS). The technical lifespan of a wind turbine (WT), generally estimated to be between 20 and 25 years, led to the initiation of the decommission phase for the earliest WTs between 2010 and 2015. Today, the recycling rate of the total mass of a WT's superstructure is between 85% and 90% [1]. However, the parts of the WT that still pose a challenge at the EoS are the wind turbine blades (WTBs). The lack of proper sustainable management for these components is preventing the wind sector from achieving a higher level of circularity and sustainability. The WTBs are made of thermoset-based glass-fibre-reinforced polymer (GFRP), a very strong and durable material that presents significant challenges when it comes to recycling. The primary reason for this difficulty is the challenge in separating the individual constituents in GFRPs (glass fibres and thermoset polymer-like epoxy) due to the crosslinks in the molecular structure of the thermoset. The volume of EoS WTBs is expected to grow substantially in the coming years, reaching a staggering 200,000 tons per year in Europe by 2050 [2]. The situation in Sweden follows this trend and will reach

25,000 tons/year by 2050 [3]. These figures have led to a growing awareness of the urgent need for sustainable solutions to manage the escalating volume of waste WTBs. Several alternatives to manage EoS WTBs at different Technology Readiness Levels (TRLs) exist (see Figure 1). When seeking to fulfil the principles of a circular economy and circulating material higher up within the waste hierarchy, solutions such as incineration or cement coprocessing (widely practiced today [4]) do not contribute to maintaining the inherent value of the WTBs; instead, most of the WTB value is lost in these processes.

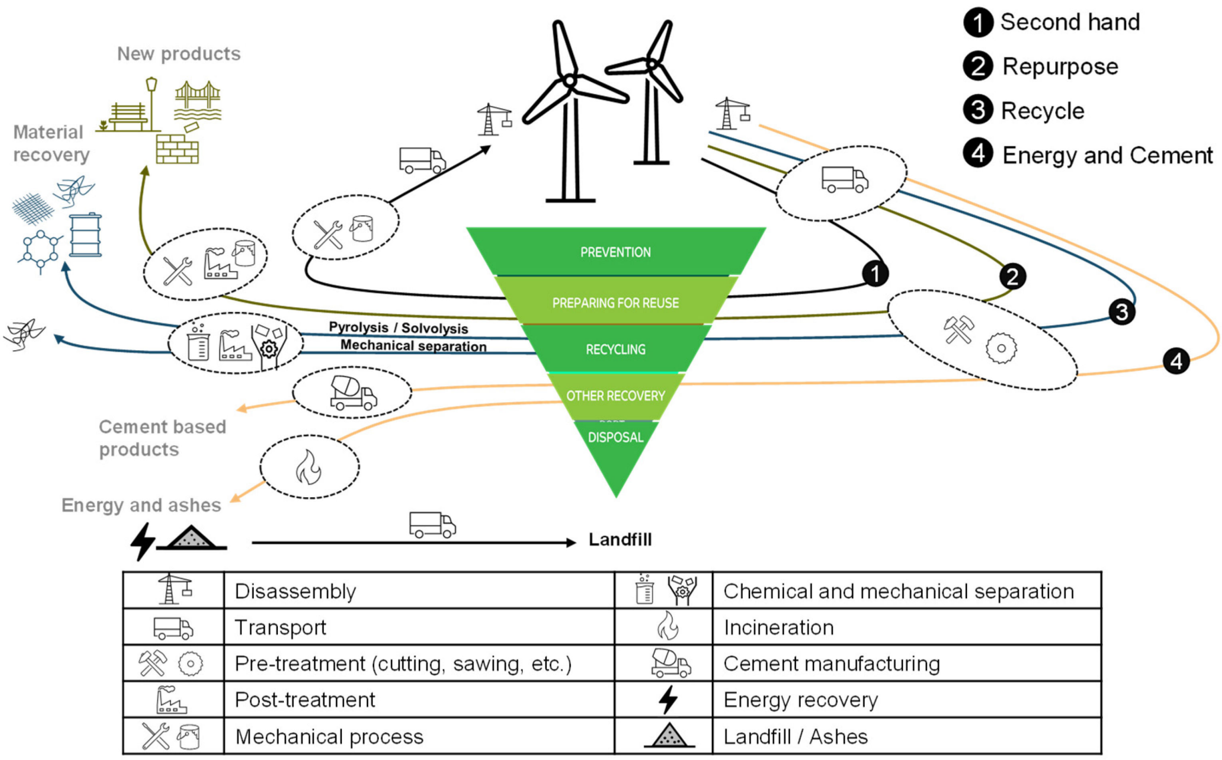

Figure 1. Different alternatives in managing WTB after decommissioning.

Realising the circularity of decommissioned WTBs can be assisted by using the ReSOLVE framework's principles, suggested by the Ellen MacArthur Foundation [5]. These are as follows:

- Regeneration of natural resources and rehabilitation of environments affected by extraction;
- Resource sharing to reduce unnecessary duplication of resource provision;
- Optimisation of current resource utilisation patterns to maximise utility and value per unit;
- Resource flows that are looped by redirecting waste flows to be used as inputs for other activities;
- Substitution of high-environmental-impact resources for low-impact ones.

Delaying the decommissioning of WTs and repurposing them for resale offer optimal circular solutions for preserving the inherent value of the WTBs. Alternatively, repurposing the WTBs in the construction of new products or structures presents the next best option.

The repurposing path has been the focus in several research projects that have been carried out during the past decade. In these projects, WTBs have been used as the base material in new conceptual designs or actual protypes [6]. Two groundbreaking large-scale demonstration projects have led to the construction of the world's first pedestrian bridges made of EoS WTBs [7–9]. Additionally, in a recent case study on repurposing decommissioned GFRP WTBs [10], life cycle analysis (LCA) tools were used and it was demonstrated that repurposing results in the lowest overall environmental impact compared to other evaluated recycling methods.

In Sweden, several research projects have focused on repurposing EoS WTBs in recent years [11,12], with the first implementation expected in 2024 [13].

The Circublade project [11], from which this research paper presents the main findings, explores WTB repurposing based on a holistic approach, focusing on three central aspects: (i) studying the value chain and the necessary logistics system, (ii) accessing data about decommissioning times and potential repurposing projects, and (iii) developing conceptual designs that align with market demand and requirements. The environmental impact of the repurposing solutions was also explored to evaluate the environmental benefits for three specific case studies.

The objectives of this paper are (1) to explore and present the demand for products made of EoS WTBs from the perspective of end-users, including the requirements related to the value chain and logistics, (2) to introduce a newly developed digital platform designed to facilitate access to EoS WTB data for emerging industrial actors within the new value chain, and (3) to present the results of three concept designs made from repurposed EoS WTBs, based on technical and sustainable analyses. This study primarily focuses on the Swedish context to gain a deeper understanding of the situation regarding EoS WTBs and the potential value chain in Sweden. However, some of the findings presented here could be applicable to other countries facing similar challenges.

2. Materials and Methods

The early value chains established to manage EoS WTBs were developed for energy recovery and cement coprocessing [3]. However, no established value chain exists today for WTB repurposing. The demonstrated potential of repurposing WTBs, the increasing number of EoS WTBs, and the growing emphasis on a circular economy are driving forces toward creating a value chain in the near future. Several elements must be considered to create a viable and sustainable value chain: (1) continuous sourcing of WTBs and quality control, (2) availability of various repurpose applications to accommodate different WTB types, (3) market demand, (4) market acceptance and cultural perceptions, (5) regulatory compliance, (6) supply chain complexity, (7) cost considerations, (8) infrastructure and logistics, and (9) scalability and expansion.

Addressing these challenges requires a holistic approach that involves collaboration across sectors, including the government, industry, academia, and engineering society. It also requires innovation, creativity, and a commitment to sustainability and social responsibility. The Circublade project [11] addresses challenges 1, 2, 3, and 8, as briefly discussed in what follows.

2.1. Logistical Challenges

Repurposing structures involves establishing and executing a procedure to relocate an EoS part to a new site for a new purpose or application. The complexity of this process depends on both technical requirements and market needs. In the case of repurposing EoS WTBs in Sweden, logistics and transportation criteria were analysed. The mapping drew from a literature review supplemented by surveys and interviews with experts. The literature review was performed according to the guidelines described in [14], which state that semi-systematic reviews are relevant when the studied topic has been approached by multiple disciplines. The findings from the literature were used to formulate the questionnaire for the interviews and surveys. The interviews were semi-structured, following the methodology suggested by [15] and which recommends interviewing high-level managers. Interviews were carried out with project managers and CEOs of the respective organisations.

2.2. Market Research and Demand

In the project, a survey using a structured questionnaire [16] with 9 questions was conducted to explore the perceptions of the public (specifically municipalities) regarding new products incorporating components of EoS 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 EoS WTB products. The questionnaire was distributed to all municipalities across Sweden, with a response rate of approximately 10%. While the questions primarily focused on pedestrian bridges, respondents were encouraged to consider alternative applications like benches and bicycle shelters.

2.3. WTB Sourcing and Digital Platform

A paramount aspect in establishing a robust value chain for EoS WTBs is related to the acquisition of information about the WTB type, availability, location, and condition. Furthermore, access to this information needs to be early enough to allow the proper planning for all parts involved. Historically, the exchange of WTB data has been limited by industrial intellectual property protections. The first step toward the standardisation of data exchange was taken in 2023, with the experimentation with the 'Blade Material Passport' across different WTB manufacturers [17]. However, further efforts from manufacturers and operators are necessary to fully exploit the potential of repurposing EoS WTBs. The website Vindbrukskollen [18] is the most comprehensive open-access database of Swedish wind farms, with over 5000 registered wind turbines. It provides important data such as geographic location, type of turbine, construction year, and owner. However, other information critical for EoS WTB management, such as planned decommissioning dates and WTB repair history, requires direct contact with WT owners.

The digital platform from [12] was further developed in the Circublade project in order to add important missing features (e.g., filters in the user interface, cutting tools, safe login, access request, routing tool for easy logistics) and reshape its architecture for increased data safety in the databases.

The objective of having a cutting software tool within the digital platform is to support the cutting process during decommissioning for optimised repurposing of WTBs. The software (version 1 at the moment) allows for the accurate cutting of the WTBs, ensuring that final product (i.e., bridge) will fulfil the necessary structural design requirements. The precision in cutting of the WTB at the decommissioning site helps in reducing the transport costs and maximising the structural efficiency of the final product.

2.4. Case Studies of Repurposing WTBs: Design Process and Challenges

Three case studies of WTB repurposing were investigated, each employing a different approach due to differences in the technical requirements for the new products. The first case study focused on repurposing a WTB section as a girder for a short-span pedestrian bridge. The final design of this short-span pedestrian bridge aimed to present a simple and affordable concept that uses over 95% waste GFRP materials.

For the second and third case studies, the WTBs that were used in the design originated form a same wind farm that was decommissioned during the course of the project; 67 WTBs of type LM 23.5 were recovered from Vestas WT.

To align with the objective of maximising the inherent value of EoS WTBs by prioritising the waste hierarchy, it is paramount to efficiently utilise the majority of the WTB structure, thereby minimising the waste volume. To achieve that goal, the development of innovative conceptual designs (or combinations of designs) is needed.

Each WTB was divided into two segments. The first segment, consisting of the 10.5 m from the WTB tip, was used to develop façade elements for a new car park building. The remaining 13 m segment, which includes the heaviest and bulkiest part of the WTB, was utilised in the development of an innovative concept of a noise barrier wall for road and railway applications.

2.5. Environmental Evaluation

Investigations into various types of case studies on the repurposing of WTB sections were carried out. Understanding the competitiveness of these designs in terms of sustainability is crucial to maximise the use of WTB sections and enable better design concept choices, aligning with the goal of a sustainable society. Therefore, evaluating the environmental impact of the different case scenarios (façade elements and noise barriers) during their life cycle is essential.

One tool used for such purpose is the life cycle assessment (LCA), which can provide valuable data for decision-makers in support of sustainable initiatives. In this study, a simplified LCA, named environmental evaluation, was performed, based on ISO14040 [19] and ISO14044 [20] standards, to estimate the environmental impact (kg CO_2-eq) of the three different WTB repurposing concepts. While estimating the sustainability of the chosen designs, the evaluation also identifies possible hotspots along the value chain, finding key factors that could affect their sustainable performance.

The goal and scope defined for this evaluation were to investigate the environmental performance of the different design concepts manufactured using repurposed WTB sections. The system boundary of the performed environmental evaluation considered processes from cradle to gate, including materials (i.e., repurposed WTBs), transport, and manufacturing. However, since the manufacture of these concepts is currently in progress, the inventory phase remains an ongoing work, and as a result, data pertaining to this stage have not yet been fully documented. The assembly of the concepts, related groundwork, the operation phase (including the maintenance), and end-of-life (EoL) management were excluded from the current study. The functional unit comprised one façade element and one noise barrier.

3. Results

3.1. Logistical Challenges and Opportunities

An essential element of repurposing products involves the establishment of a functional take-back logistical system. WTBs are large and heavy, so efficient logistics are important to keep time and costs down. The critical factors identified as influencing logistics include the accessibility of the WTBs, their dimensions and weight, preparation requirements prior to transportation, necessary machinery, transport distance, permits required, and environmental considerations.

The site where the WTBs are located influences machinery accessibility. Without adequate infrastructure, additional efforts like road reinforcement are required (from discussion with a DSV project manager). The size of the WTBs also impacts the logistics, which is a factor that differs between countries. In Sweden, if the load is shorter than 30 m, it does not require a permit [21]. Since the length of WTBs being dismantled today generally does not exceed 30 m, this is not currently a significant problem (from discussion with a high level manager at Business in Wind).

Processing the WTBs on-site tends to be both time-consuming and costly. Generally, it is more efficient to transport the WTBs to a location where they can be managed within a controlled facility. However, in some cases, it is beneficial to cut the WTBs on-site to make it easier to transport them, thereby reducing transport costs.

Even though for most of the actors interviewed, it is currently more economical to cut the WTBs in a controlled environment, most companies that were interviewed stated that they were developing methods to cut WTBs on-site as they expect transport prices to increase in the future. Currently, transportation costs can account for up to 30% of the total cost for a repurposed product (from discussion with a project Manager, Anmet).

The required machinery, especially cranes, is another aspect impacting costs. The main cost for the crane does not come from the lifting itself, but from setting up the crane, which can take hours, compared to the lifting, which can take just a few minutes (from discussion with a purchasing and logistics manager at Kingo Wind (Silkeborg, Denmark)).

Prior to transporting the WTBs, it is necessary to acquire relevant transport and environmental permits. Most importantly, if the WTBs are meant to be transported within the EU, a permit for transportation of waste between countries is essential. At the present (2024), this permit can take up to a year to obtain. Since the WTBs are currently classified as waste rather than products meant for repurposing, there is a requirement to obtain such a permit before transporting the WTBs between EU borders (from discussion with a project manager at Anmet and a purchasing and logistic manager at Kingo Wind).

3.2. Market Demand

Pedestrian and bicycle bridges are crucial for safe passage across obstacles like roads and rivers, enhancing urban safety, accessibility, and sustainability. However, to ensure their continued functionality and safety, regular maintenance is essential. Costs associated with maintenance activities of pedestrian and bicycle bridges constitute a large portion of the life cycle cost of these structures.

Studies have demonstrated that fibre-reinforced polymer (FRP) bridges exhibit considerably reduced maintenance requirements and costs compared to bridges made of traditional materials such as concrete and steel [22]. This finding underscores the potential of FRP bridges to revolutionise the construction of municipal infrastructure by reducing high maintenance costs and offering easy-to-manufacture, lightweight structures.

EoS WTBs present a promising solution for the sustainable construction of FRP bridges. Incorporating EoS WTBs into the design and manufacture of GFRP bridges allows municipalities to minimise waste and leverage available resources, resulting in resilient and eco-friendly infrastructure.

A survey conducted with Swedish municipalities 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.

Given the proven durability and reduced maintenance needs of FRP bridges, municipalities emerge as a prime market for the adoption of this innovative infrastructural solution. By transitioning to FRP bridges made from EoS WTBs, municipalities can mitigate maintenance costs while ensuring the longevity and reliability of their infrastructural networks.

3.3. WTB Sourcing and Leveraging Digital Tools

Based on the existing Swedish wind park database Vindbrukskollen [18], an inventory and study of existing WTs in Sweden was conducted. This study shows that in the next 20 years, approximately 15,000 WTBs will reach EoS status. Different types of WTs are installed in Sweden, meaning there are different types of WTBs. This is also an important parameter to consider in the process of repurposing EoS WTBs as their structure and material composition may differ significantly. One-quarter (25%) of the WTBs reaching the EoS between 2020 and 2030 will come from a Vestas V90 WT. This presents opportunities to develop waste management methods tailored to this particular WTB type, potentially leading to more efficient and cost-effective processes. Moreover, the distribution of WTB waste is not expected to be uniform across Sweden. The southwest of Sweden is projected to account for the majority of the waste volume until 2030, while the northern regions are expected to generate the majority of waste volumes at a later stage (Figure 2).

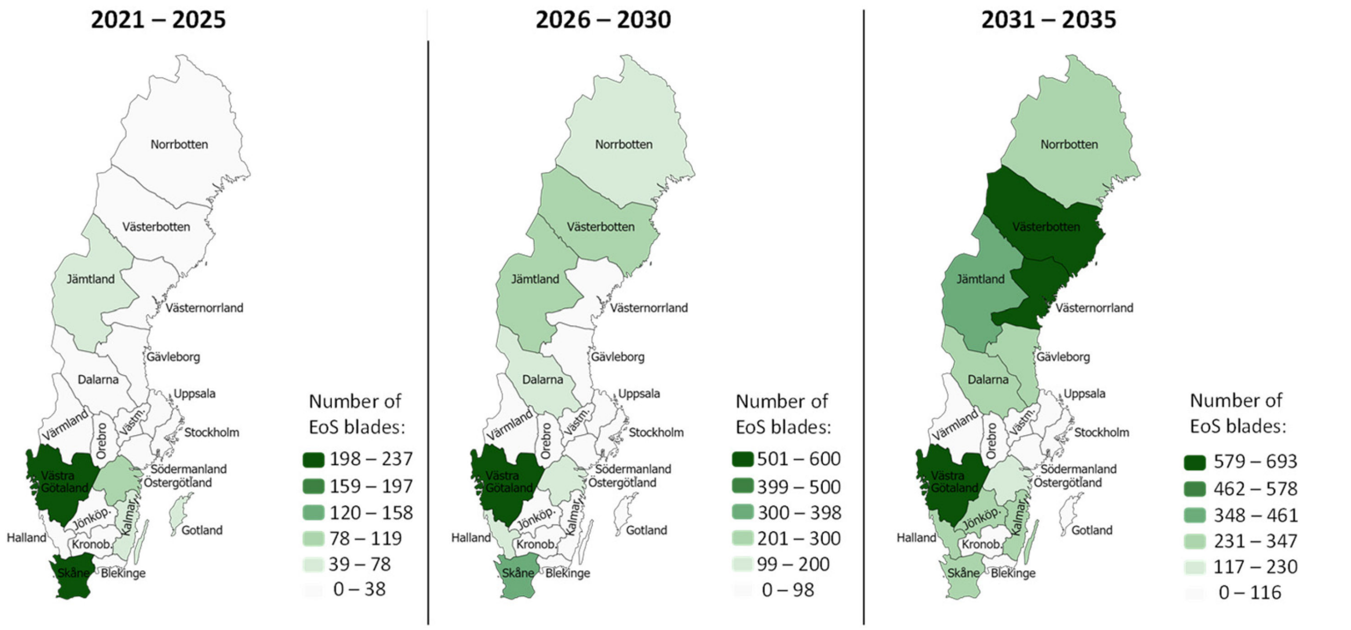

Figure 2. Mapping EoS WTBs in Sweden from the estimated decommission year.

At the present, permitting is a digital process in most municipalities, and digital design and BIM (building information modelling) are widely practiced in construction projects. The intersection of these technologies can be realised on a digital platform to build the intended framework. Additionally, digital platforms act as a hub to facilitate and accelerate the creation of contacts between the different partners along the value chain (e.g., WT operators, WTB owners, decommissioning companies, potential actors working with repurposing of WTBs, logistic companies). For instance, the digital platform is expected to facilitate the exchange of materials and reduce the cost of their transportation. Online marketplaces specialising in building materials can enable contractors, architects, and designers to source materials from existing structures, promoting the circular economy and reducing the demand for new materials.

A logical workflow of the developed digital platform in the Circublade project is shown in Figure 3. Such a digital platform has two main objectives: (i) to accurately estimate the quantities of different WTB waste streams for various WT types, and (ii) to provide optimal management strategies for all generated waste streams based on economic and environmental criteria.

In this platform, several important features and components are accounted for, such as (1) user identification and user needs at different stage of the value chain, (2) data security and safety features to access WTB data stored in the databases, (3) advanced search and filter functionality, (4) the possibility to initiate contact between suppliers and buyers, (5) providing sustainable transport options, and (6) impact tracking by measuring the sustainability indicators.

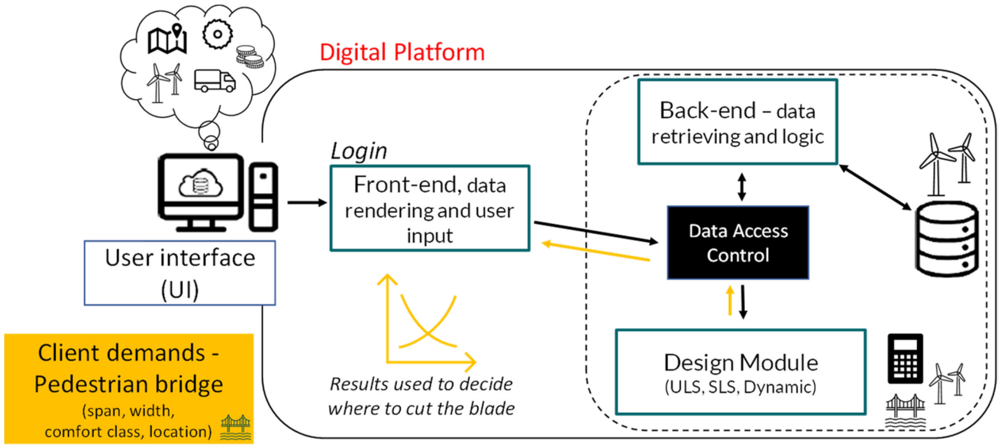

Figure 3. Digital platform: logical workflow.

The digital platform architecture (Figure 4) is designed using a layered architecture approach where functional requirements are implemented as microservices. The main layers of the architecture are a (i) Persistent Layer (storing user data, login information, and details about WTBs), (ii) Microservices Layer (data handling, and management of WTB-related information, including secure sharing functionalities), and (iii) API (Application Programming Interface) Gateway Layer (presents all microservices to end-users in a structured manner).

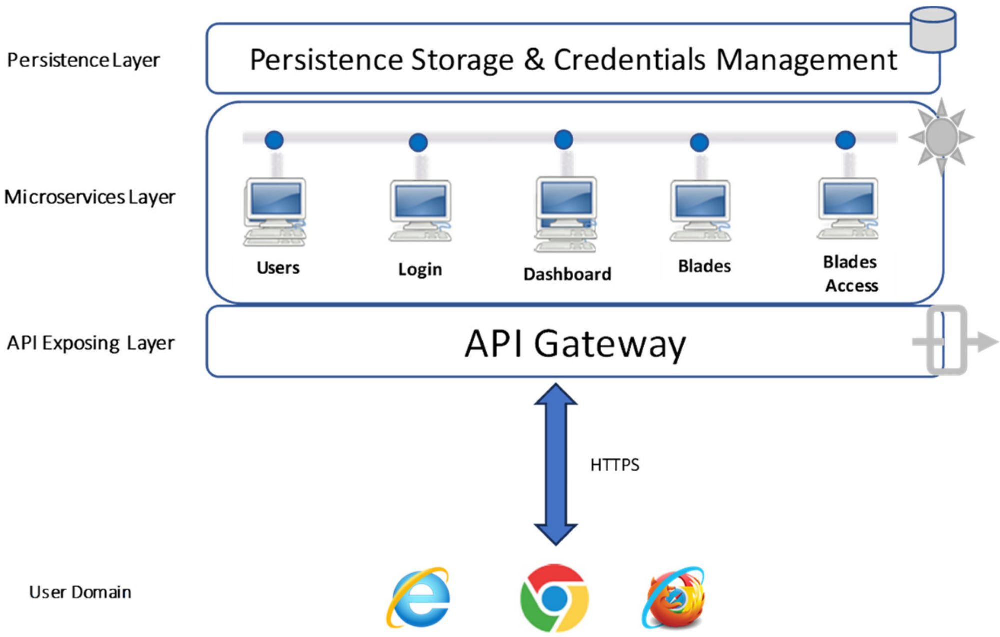

Figure 4. Digital platform architecture: layered model.

To enhance the interaction between end-users and functional microservices, a user experience (UX)-based dashboard has been developed. This dashboard serves as a user-friendly interface, providing functionalities such as user registration, authentication, authorisation (sharing blade data), and the management of various microservice-exposed data. This user-centric design aims to streamline the user experience, making it more intuitive and efficient when accessing and utilising the functionalities offered by the microservices. Through the dashboard, end-users can easily navigate and interact with the diverse range of microservices, fostering a seamless and user-friendly environment for managing data and accessing services in secure manner.

The WTB cutting software developed in this project is a finite-element-based structural analysis program developed in MATLAB R2018 software and engineered to facilitate the precise in situ cutting of the WTBs for the fabrication of pedestrian bridges. This software provides a thorough analysis of the structural properties of a bridge made from a WTB as the main load-bearing element, tailored to the specified length and dimensions specified by the user. It encompasses three main types of analyses: frequency analysis, dynamic analysis, and static analysis.

- Frequency analysis: This aspect of the software evaluates the vibrational behaviour of the bridge. It identifies the natural frequencies of the structure to ensure that they do not coincide with critical ranges specified by the relevant design code [23], which could lead to resonance and potential structural failure.
- Dynamic analysis: This component examines the response of the bridge to time-dependent pedestrian loads. It assesses how the structure will perform under varying conditions, by calculating the maximum acceleration response and comparing it with thresholds specified by codes [23], ensuring that it the bridge fulfils the intended comfort level for users.
- Static analysis: This analysis assesses the bridge's ability to comply with limits set on deflections due to self-weight and live loads. It ensures that the design complies with requirements in the serviceability limit state.

3.4. Case Studies of Repurposing WTBs: Design Process and Challenges

Illustrations of the case studies that were investigated in the Circublade project are shown in Figure 5 (short-span pedestrian bridge with WTB section repurposed as a girder) and Figure 6 (car park building with wall elements made of WTB sections, and noise barrier wall made of WTB sections).

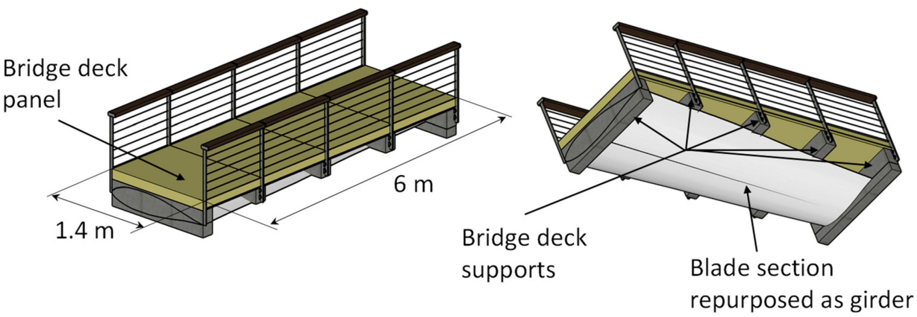

Figure 5. Case studies of EoS WTB repurposing in Sweden: short-span pedestrian bridge (illustration, main components, and dimensions).

Figure 6. Case studies of EoS WTB repurposing in Sweden: façade elements for car park building (**left**) and noise barrier (**right**) (pictures from Lloyd's Arkitektkontor, Sweden).

The first case study is a short-span pedestrian bridge where a section of a WTB of type NWP28.3 ATV has been used as a girder. The WTB is 28.3 m long, with an approximately 4 m long rotating tip (air brake). The section that was cut from the WTB is the 6 m long section after the tip (see Figure 7).

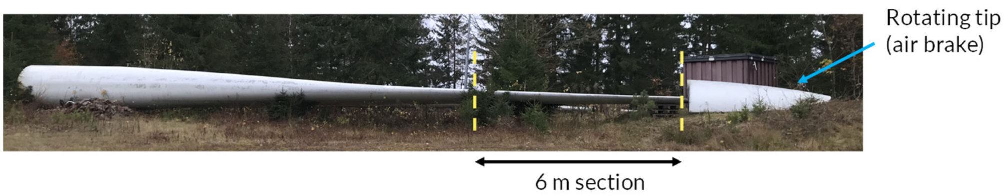

Figure 7. NWP28.3 ATV WTB and section cut for WTB repurposing as bridge girder.

This WTB type has an I-beam internal structure, and both a GFRP (glass-fibre-reinforced polymer) and CFRP (carbon-fibre-reinforced polymer) are used in the structure. Detailed section data along the WTB length were obtained from the manufacturer in a previous study [24] and were used in the structural analysis. Preliminary finite element (FE) models were built using the commercial FE software Abaqus version 2023 [25] to study the deflection of the bridge. The design load used corresponded to a Traffic Class 4 [26], with live loads of 2000 N/m^2 and a dead load (WTB section and bridge deck weight) of 1800 N/m^2 (28 kN in total). The weight of the bridge deck supports, custom made to fit the curvature of the WTB, were also included in the total load.

In terms of deflection, the maximum allowed at the SLS (Serviceability Limit State) is L/400 = 6000/400 = 15 mm. The maximum deflection observed (5.06 mm, see Figure 8) is much lower, which means that the deflection fulfils the regulations in terms of the SLS.

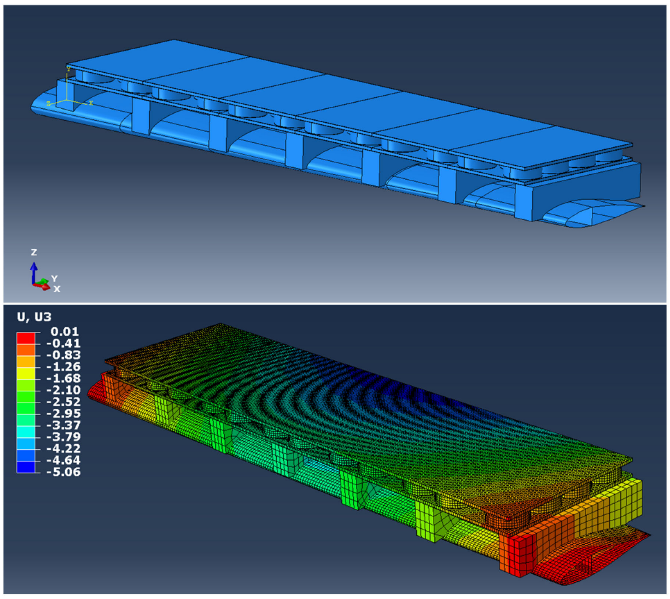

Figure 8. FE model assembly of the pedestrian bridge and contour plot of the deflection under loading (3800 N/m^2).

In this preliminary numerical model, the stress levels observed (from +30 MPa to −30 MPa) are moderate in relation to the material strength, which indicates that damage initiation under this load level is not expected to occur. However, further analysis of the 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 1 show that requirements in terms of acceleration and frequency are met.

Table 1. Results of the frequency analysis using the cutting tool for the bridge made of a WTB section.

Vertical Frequencies	Critical Ranges
Frequency Mode 1 (Hz) = 7.0	First mode 1.25 Hz $\leq$ f $\leq$ 2.3 Hz Second mode 2.5 Hz $\leq$ f $\leq$ 4.6 Hz
Frequency Mode 2 (Hz) = 28.0	
Horizontal Frequencies	**Critical Ranges**
Frequency Mode 1 (Hz) = 18.2	0.5 Hz $\leq$ f $\leq$ 1.2 Hz
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 behaviour of the bridges is expected.

The other case studies, namely the façade elements and the noise barrier shown in Figure 6, were conducted with a focus on optimising the cutting and repurposing of the EoS WTBs. In this context, the WTBs were cut to facilitate the extraction of sections for both case studies. The bulky and heavy root-end (13 m) was used for the noise barrier concept, while the relatively lighter and thinner tip-end (10.5 m) was repurposed for the façade element concept (see Figure 9).

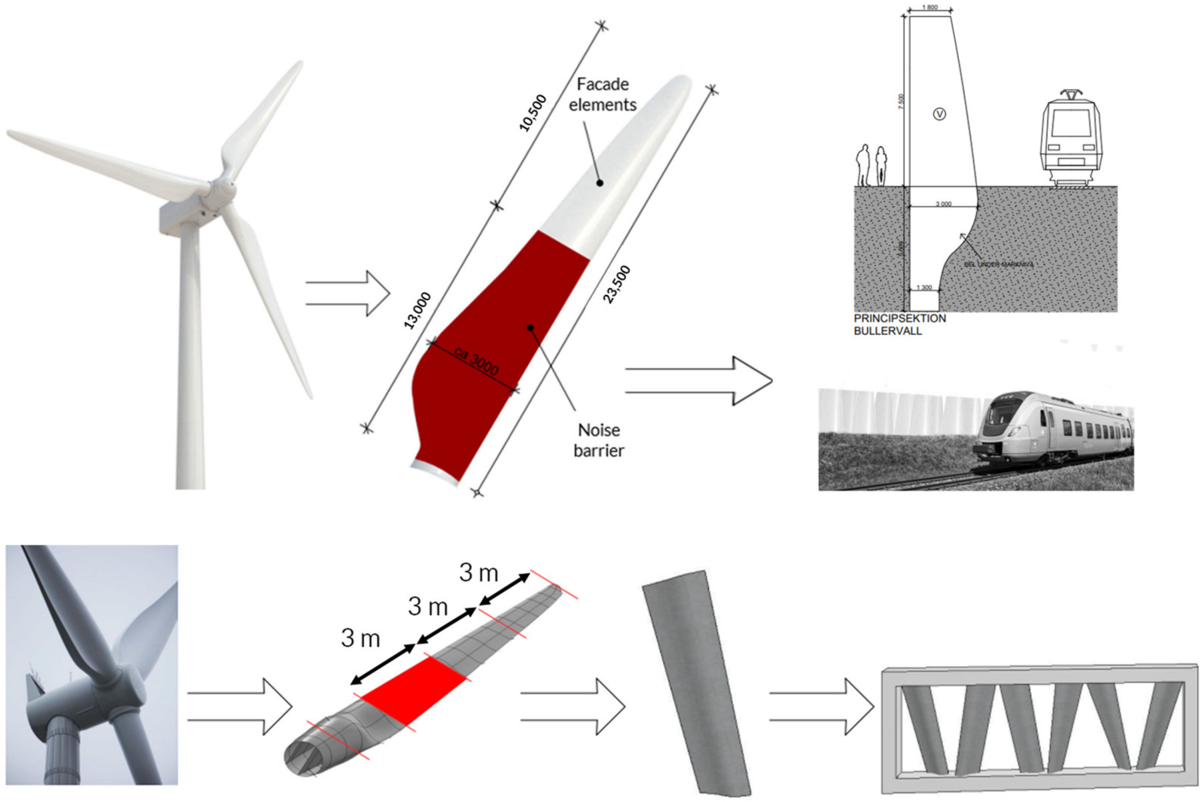

Figure 9. Case studies of EoS WTB repurposing in Sweden: optimised cutting of the blades for repurposing as façade elements for car park building and noise barrier (pictures from Lloyd's Arkitektkontor, Sweden).

These two last case studies are still under development but at different stages. For the noise barrier concept, discussions with a potential end-user are ongoing. Questions related to procurement processes and technical performance in terms of noise insulation have been raised and studied. For the other end of the WTB, the car park building concept has been brought much closer to realisation as the construction is expected within a year in the city of Lund, Sweden. Approximately 170 sections of WTBs (3 m each) will be used for the façade of the building.

3.5. Environmental Evaluation

In this study, a cradle-to-gate environmental evaluation of the concepts (façade elements and noise barrier) was performed. The input data for mapping the processes were sourced through interviews with the project partners (Fair Wind, Kingo Recycling, Composite Design, and Lloyd's Arkitektkontor).

As a result, detailed process flowcharts for each concept were developed. In Figure 10, a representative concept for a noise barrier is shown. The processes analysed in the study included the repurposed WTB activities (cutting, sawing, grinding, and waste management), manufacturing (including materials other than WTBs and pre-treatment of the WTBs), and transportation (materials and manufactured components). Outside of the scope were the materials and processes connected to the pipes, rods, bolts, and foundation, as well as the actions related to the WTBs' decommissioning, on-site assembly, maintenance, and EoL.

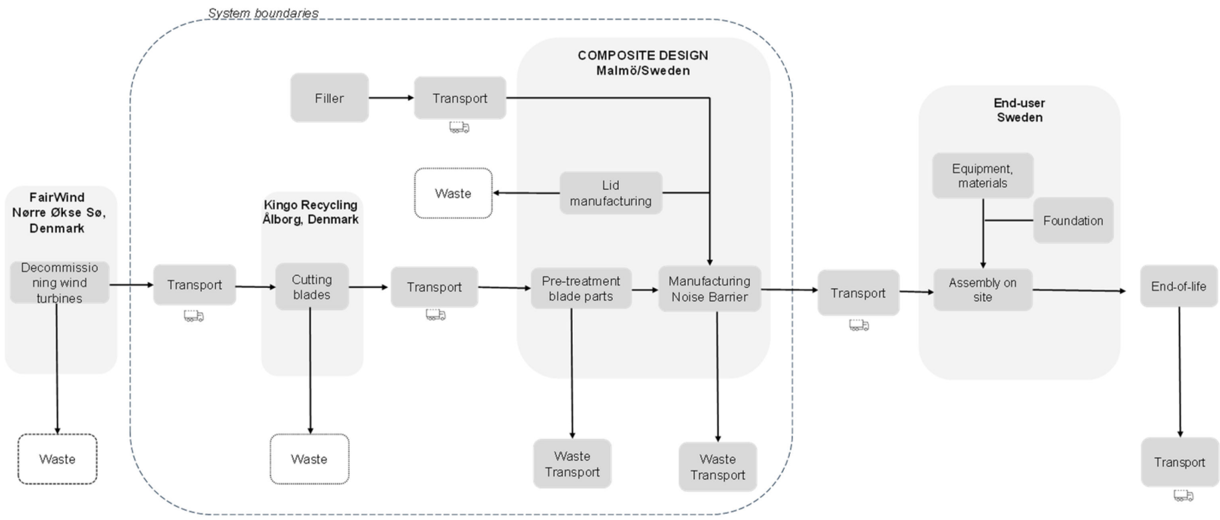

Figure 10. System boundaries of the noise barrier concept.

The decommissioning of the WTs took place at FairWind farm, located in Nørre Økse Sø, Denmark. After decommissioning, the WTBs were detached from the WTs. These 25 m WTBs were repurposed as components (secondary materials) for two of the three aforementioned concepts.

The WTBs (approximately 3574 kg each) were loaded on a truck (a 60-metric-ton with a flatbed semi-trailer) using a wheel loader (capacity 17 tons) and transported about 33.5 km to Kingo Recycling, located in Ålborg, Denmark, where the cutting step took place. No waste was expected from the decommissioning process.

The cutting of the WTBs was performed by Kingo Recycling using a diamond cut saw (Hilti DS-BG 80) with the support of an excavator (capacity 40 tons) and a lifting device (capacity 17 tons) to carry and load the WTB parts onto a truck for transport. From the 25 m length, 12 m (approximately 714 kg), starting from the WTB tip, was used for the façade element concept (see Figure 6 (left)). The 12 m section was cut into 3 m parts. These 3 m parts were then transported 473 km by truck (lorry 16–32 metric tons) to Lloyd's Arkitektkontor AB, located in Lund, Sweden.

The remaining 13 m of the WTB (approximately 2860 kg) was cut into sections of approximately 4 m each. At the moment, the foreseen route is to transport these sections by truck to Composite Design, Malmö, Sweden (457 km). Composite Design used these parts for manufacturing the noise barrier concept (see Figure 6 (right)). The waste generated during the cutting process was mostly water and dust.

Before manufacturing, repair of the WTBs may be necessary due to potential damage incurred during the decommissioning, cutting, and/or transport steps.

In addition to the GFRP WTB parts, steel pipes, rods, bolts, stainless steel sheets, glue, and concrete beams were used to manufacture the façade elements. Steps such as drilling, welding, and painting were also included. For the noise barrier, the manufacturing steps included sealing the bottom of the part with repurposed WTB material, filling the 4 m WTB part for stability and security reasons, lid manufacturing (also using repurposed WTB material), and sealing (using an epoxy-based glue).

Variability and uncertainty, as well as the limited availability of data, made the inventory work a demanding task, though it is usually crucial for the accuracy and reliability of the environmental evaluation results.

The inventory analysis was based on primary data, collected from the project partners, and generic data, from the Ecoinvent 3.10 database (represented in general global, European, or Swedish averages) and the literature. Data regarding materials, electricity, and transport were collected between 2023 and 2024, and their respective values for climate change (GWP 100), expressed in CO_2-eq, were obtained from Ecoinvent and the literature. The inventory is an iterative process, where data undergo continual review and refinement throughout the manufacturing stages to ensure their accuracy and relevance.

The environmental impact (kg CO_2-eq) from cradle to gate of the façade elements and noise barrier concepts was divided into three steps: WTB cutting, transport, and manufacturing. However, as previously mentioned, since the manufacture of these concepts is currently in progress, the results pertaining to this step will not be presented.

The total environmental impact for the cutting is estimated at 5.4 kg CO_2-eq/WTB/cutting. This figure accounts for the fuel consumption of the diesel generator, and the use of a saw, an excavator, and a wheel loader during the process. Transporting one 25 m WTB (3574 kg) to the cutting location results in approximately 23 kg CO_2-eq. After cutting, the CO_2-eq for transporting the WTB parts to the manufacturing location results in approximately 251 kg CO_2-eq for the noise barrier concept (approximately 2860 kg for 457 km) and 65 kg CO_2-eq for the façade element concepts (approximately 714 kg for 473 km).

An analysis of the processes involving decommissioning, transportation, and cutting revealed opportunities for methodological enhancements. It is recommended to segment the 25 m WTB into reusable lengths directly at the decommissioning site—approx. 4 m for the noise barrier and 3 m for the façade elements. This approach could streamline logistics and potentially decrease the environmental impact associated with these activities, as it would allow for the use of a smaller truck without the flatbed semi-trailer attached.

For future considerations, it is advisable to incorporate logistical optimisation into the 'cradle-to-gate' analysis. This could involve situating the manufacturers of the concepts in proximity to the wind turbine farms. Such a measure would not only streamline the supply chain but also lower the transportation-related carbon footprint, which is expected to be the primary source of environmental impact in the life cycle of the concepts. Minimising the distance between the point of decommissioning, cutting, and manufacture is expected to achieve a more sustainable model that aligns with environmental conservation goals. This approach underscores the importance of geographic considerations in reducing the overall environmental impact.

3.6. Regulations and Policies

The role of regulations is crucial in the repurposing of WTBs by setting targets, providing guidance, and establishing standards for waste management and repurposing practices. Waste management is generally a cooperative effort involving different levels of jurisdiction from municipal to regional. Areas that governments and policymakers can play a role in include, but are not limited to, (a) mandating waste reduction and recycling targets, (b) encouraging the use of recycled materials by subsidising and incentivising, (c) providing guidance on waste management practices, (d) creating a permitting process for waste management facilities to ensure that they meet certain standards and are operated in an environmentally responsible manner, and (e) establishing product standards to ensure their safety and performance, to increase confidence in repurposed materials and encourage their use. Introducing mandatory recycling targets of WTBs, or a ban on landfilling, incentivises

WTB owners to find innovative methods for the EoL WTBs, such as repurposing them for other structures.

In addition to these measures, regulatory actors can impact the uptake of repurposed products by reviewing and updating current legislation to ensure it does not hinder repurposing. As exemplified above in the logistics section, transporting WTBs across EU borders requires a permit that can take up to a year to acquire. Reviewing current regulations to allow for WTBs to be classified as a product instead of as waste could be an efficient legislative tool to facilitate the acceptance of repurposed products, such as WTBs, making them a more viable option for consumers.

4. Discussion and Conclusions

Investigating how the municipalities and public perceive new innovative infrastructure and architectural products is an important step towards facilitating the integration of products made of EoS WTBs (End-of-Service wind turbine blades) in the future. Although there might be some gaps in knowledge about the possibilities and advantages of these repurposed materials, many of the municipalities expressed an interest and were open to testing new applications. However, it is essential to certify that the new applications meet the same standards and requirements as infrastructure made from traditional materials.

The machinery and transport of repurposed WTBs significantly impact the final cost of repurposing projects. As transportation costs have risen and can constitute as much as 30% of the entire project costs, minimising these expenses is a key aspect of keeping the total cost manageable. In the future, as EoS WTBs become more common, the logistical system has to be improved, a point highlighted in interviews with experts. Centralised production could enhance process efficiency, but large-scale viability requires streamlined transportation of WTBs across EU borders. Currently, decommissioned WTBs are classified as waste, necessitating lengthy permit processes for transport.

A potential solution would be to reclassify WTBs intended for repurposing as products rather than waste, reducing transportation lead times. However, it is essential to weigh the benefits of large-scale processing facilities against local production facilities. Environmental analysis shows that transportation is a large contributor to the repurposed WTBs' CO_2-eq emissions. Transportation also has a significant impact on the total cost of logistics.

A digital platform to ease the management of EoS WTBs has been further developed. This digital platform objective is to catalogue all WTBs in Sweden, together with relevant data needed for repurposing activities after EoS. The architecture of the digital platform has been designed around the concept of data security and safety. Many sensitive data on WTBs (structure, material type, repair history, decommission year, etc.) should be protected and yet still be available for effective repurposing. Today, WTB data are accessible upon request to the blade owner.

Adding practical digital tools (such as a cutting/calculation tool and a routing tool) to the digital platform has also been initiated. The main objective is to minimise the challenges encountered in-between the WTB decommissioning process and the repurposing process, thereby facilitating the establishment of new value chains for WTB repurposing. These digital tools include simplified life cycle cost calculations and a WTB cutting guide software with preliminary structural analysis (i.e., the optimised cutting section for a specific repurposing application).

Transporting waste materials to repurposing sites generates emissions. By conducting a life cycle analysis (LCA), it is possible to quantify the environmental impact of reusing the WTBs and determine the 'green' distance by comparing the impact of reusing versus using virgin materials. To ensure that reusing construction waste materials is performed in a sustainable and environmentally responsible way, it is necessary to include the LCA in the digital platform in future developments.

As a large and increasing number of WTs reach their decommissioning phase, there is an urgent need to establish proper value chains to sustainably manage their components. This is specifically true, and challenging, for the WTBs. The solutions suggested in the

Circublade project focus on the repurposing alternatives, which are expected to keep most of the inherent value of the WTBs. Innovative products made of decommissioned WTBs such as pedestrian bridges, façade elements, and noise barriers have been the focus of the investigations. However, significant challenges remain, particularly in the following areas:

- Lack of awareness and knowledge: many construction companies, builders, and contractors may not be aware of the benefits of reusing WTBs or may not have the knowledge and expertise to implement reuse effectively;
- Cultural factors: cultural attitudes and perceptions towards using recycled or repurposed materials may discourage the uptake of WTB repurposing in certain regions or communities;
- Quality concerns: there may be concerns about the quality of EoS WTB materials, including potential contamination, which can limit their repurposing in certain applications;
- Regulatory barriers: regulatory frameworks and policies do not support the repurposing of WTBs, making it difficult to obtain the necessary permits and approvals;
- Logistics and transportation: the logistics and transportation of WTBs can be complex, particularly for large volumes, making it challenging to move materials to the appropriate repurposing facilities;
- Economic factors: the cost of transporting, sorting, and processing EoS WTBs can be high, making it less economically viable than using virgin materials;
- Lack of infrastructure: the lack of appropriate infrastructure, such as sorting, processing, and storage facilities, can make it difficult to effectively upcycle decommissioned WTBs.

For a genuine circular economy to develop, these challenges need to be addressed at a system level in multiple stages along the value chain. Achieving this will require a large-scale transition including policy and public service modifications, identifying and leveraging large-scale commercial opportunities and circular business models, investment in technological progress, and changes in consumer behaviour, to ensure that the entire life cycles of built environment materials are designed with circularity in mind. The challenges for this transition must be addressed at different levels, including research projects and the development and implementation of new policies that will support the emergence of new circular value chains. From a technical standpoint, robust, reliable, and standardised quality processes for EoS WTBs must be established to ensure their safe repurposing into new products. Additionally, the digital platform plays a crucial role and must be accessible online and extended to other countries. Before its public release, further research is needed to finetune the platform's various features.

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