INTEGRATING END-OF-LIFE WIND TURBINE BLADES INTO VARIOUS BUILDING LAYERS THROUGH MULTIPLE-USE CYCLES – A STRATEGY TO MAXIMISE THE LIFETIME OF WASTED MATERIALS; A CASE STUDY IN EEMSHAVEN

Nguyen Binh Minh
Faculty of Architecture & the Built Environment, Delft University of Technology
Julianalaan 134, 2628BL Delft

ABSTRACT

An increasing massive volume of wind turbine blades are coming to end-of-life in the Netherlands. These components contain mostly fibre-reinforced plastics, which has been banned from landfill and incineration. Since then, companies and institutions have spent their efforts to expand the lifetime of this material by developing a circular wind hub with various circular strategies. While some strategies, such as recycling or recovery, are less desirable due to low-quality outcomes and environmental pollution, repurposing seems to be a potential option, which uses decommissioned blades in certain products, such as building elements in one-off applications. This strategy can be enhanced by reprocessing the applications through multiple-use cycles. This research will investigate that concept based on the building layers principle to figure out its feasibility and the potential to extend the lifetime of the end-of-life material.

KEYWORDS: *wind farm, wind turbine blade, end of life, fibre-reinforced plastics, circular strategy, circularity, building layers, life cycle.*

I. INTRODUCTION

1.1. Problem statement

1.1.1. The role of wind power and the waste of wind turbine blades

The implementation of wind power plays a central role in the Netherlands. The country aims to achieve a decrease in CO2 emissions of 55% by 2030 compared to 1990 levels (Boffey, 2021) and climate neutrality by 2050 (Ministerie van Infrastructuur en Waterstaat, 2023). Wind energy is one of the most cost-effective ways to achieve that goal (Jani et al., 2020). Nevertheless, wind power's growth has also led to major environmental problems. Approximately 43 million tons of wind turbine blades (WTB) are projected to enter the global stream by 2050 (Liu & Barlow., 2017).

One of the main reasons is the fast development of the global wind industry regarding the number of turbines, and their sizes (Larsen, 2019), which are 100 times those in 1980, according to the Global Wind Energy Council. Design and certification guidelines stipulate a life span of 20 to 25 years (Germanischer Lloyd, 2010; WindEurope, 2017), but decommissioning WTB is often primarily an economic decision (Tazi et al., 2019). Another cause is the composition of blades, which contain polymer composite reinforced with mainly glass fibre, some carbon fibre, and a hybrid combination of them (Liu & Barlow, 2017). These fibre-reinforced plastics (FRP) are difficult to decompose (Saidi et al., 2022).

The lack of viable recycling options meant that a large number of WTB has been landfilled or incinerated (Schmid et al., 2020; van der Meulen et al., 2020). These are the least preferred solutions in terms of the circular economy (Scheepens, 2021). In the Netherlands, this option is officially forbidden (Scheepens, 2021). These rigorous restrictions are intended to drive the industry to seek potential resolutions. Researchers are working to develop improved methods for separating resins from fibres (Jani et al., 2022). It will take at least one decade to do that on a large scale, said Kroll in an interview with De Groene Amsterdammer.

1.1.2. A brief of multiple circular strategies for end-of-life wind turbine blades

A research from Uitvoeringsprogramma Circulaire Maakindustrie has determined the circular strategies for processing EoL WTB based on the R-ladder. R1-Refuse, Rethink, and R2-Reduce strategies could not be adapted. R3-Re-use also could not be applied due to short-term cost considerations of the product. R4-Repair is difficult due to the permit period of WTB. R5-Refurbishing is feasible to increase a turbine's yield and extend the useful life of the other parts. R6-Remanufacture is possible for small parts in turbines but is less common for parts with a greater space requirement, such as the blades, because the cost of a new product is often lower. R7-Repurpose has been developed from sympathetic but low-impact solutions to speculative but with the potential for large-scale application. Some blade repurposing concepts are also shown in current publications, such as housing (Bank et al., 2018) and bridges (Jensen & Skelton, 2018; Speksnijder, 2018). R8-Recycle, with mechanical, thermal and chemical methods, transformed the blades into low-quality products. Polluting and energy-consuming processes are required in these methods to arrive at new raw materials. R9-Recover processes, such as incineration, are not desirable. These applicable R-strategies require the development of a circular wind hub in the Netherlands to better fit the expected return volumes of EoL WTB inside a circular economy (Scheepens, 2021).

1.1.3. A potential to integrate end-of-life wind turbine blades into building layers

Designing buildings out of waste and keeping products and materials in use at the highest possible value is the core principle of a Circular Economy (CE). This process reuses the material as large parts or construction elements (Joustra et al., 2021). Such reuse or repurposing of (partial) components is preferred over recycling (Allwood et al., 2011; van Buren et al., 2016).

Fibre-reinforced polymer composites are commonly used in WTB (Jani et al., 2022). This material has demonstrated its value and feasibility for infrastructure and architecture, such as footbridges, traffic deck panels, traffic bridges, renovation (lightweight lifetime extension), cladding, edge elements, and roof structures, according to Royal Haskoning DHV. A report from Liesbeth Tromp and her group in 2016 shows that benefits associated with using FRP in buildings and civil engineering works are: high quality of the finished structure and adaptability for a wide range of accessory solutions, such as roof, façade cladding, and bridge edge elements. The report also showed a trend of using composite structures realised with fibre-reinforced polymers or plastics over the last twenty years, both within and outside Europe. This increasing number of structural FRP applications has led to a growing interest from researchers worldwide.

For EoL WTB, current structural analysis through segmentation shows that the retrieved materials have excellent properties compared to conventional construction materials (Joustra et al., 2021). Research by Simon Pronk in 2022 has proved that EoL WTB can be repurposed as construction elements by projecting desired dimensions on the blade panels. The resulting elements can be used in various applications. Spar caps made out of GFRP with uniaxial fibres. This material has a high strength and stiffness in the longitudinal direction. The modulus of elasticity is around three times higher than structural timber. Therefore, these spar caps used in the investigated blade are appropriate for structural beams. The shear web is a sandwich material with GFRP skins. The sandwich layup is characterised by high stiffness and low weight, and the foam has good thermal conductivity properties. They will suit building cladding or walls, or flooring.

The evidence above shows that potential elements for repurposing EoL WTB are structure, roofs, and cladding. These were categorised as different building layers, according to Duffy 1998, and Brand 1995, respectively. If each element or layer is demountable, the material can be repurposed multiple times. Design for multiple-use cycles is an essential step that should be taken into account in the original blade design (Joustra et al., 2021). This argument is in line with Circular Economy principles, which emphasise the importance of systems thinking and designing for multiple-use cycles (Ellen MacArthur Foundation, 2013). It has been managed by not reusing the EoL product as an entity only once but by planning versatile subsequent life cycles for it.

1.2. Objectives

Based on the inputs mentioned above, there is a potential to repurpose EoL WTB into building layers through multiple-use cycles. The longer life cycles we can expand for EoL WTB, the more time we will be able to find methods to extract glass fibres and carbon fibres out of the composite materials. The buildings, now with their layers, can be considered as multiple banks for EoL WTB; this is in line with the concept of 'building as material bank' (BAMB) from Community Research and Development Information Service (CORDIS) to prevent construction and demolition waste.

The research aims to elaborate on that repurposing solution by investigating its feasibility and the potential lifetime when EoL WTB act as parts of buildings. The focused location is in Eemshaven, one of four ports in the Netherlands that are used for installing and dismantling WTB. Required data for the research includes the quantity of upcoming EoL WTB in and around that area, the possibilities to repurpose them to building elements, and the number of years they will perform well in different use cycles.

The mechanical process, including cutting and polishing, is the primary circular method to repurpose the material. This method will be clarified more in sub-section 2.3. The proposal will be investigated with a hypothesis that a circular hub for EoL WTB has been developed in the Netherlands with the necessary facilities and mechanical techniques. This concept will be elaborated more in sub-section 2.4. Multiple-use cycles for WTB are based on the principle of building layers, which is in sub-section 2.5. Data related to functions or programmes for buildings made of EoL WTB are part of the design process, thus, are not in the scope of the research.

1.3. Research question

How can the lifecycle of end-of-life wind turbine blades (EoL WTB) be maximised by integrating them into various building layers through multiple-use cycles?

Sub-questions:

a) When and where will the upcoming WTB be decommissioned in and around Eemshaven?

b) How are the potential outcomes of each building's element made of those EoL WTB, in terms of the possibility and other aspects?

c) How long can we expand the lifetime of EoL WTB in Eemshaven through this method?

1.4. Research structure

The background material in this study initially discusses the circularity, the turbine blades, and the principles of building layers in Section II. The methodologies of applied research and the information needs are covered in Section III. Then Section IV presents the findings based on those research methods. The analysis of results, answers to the research questions, and a discussion will be provided in Section V as a conclusion.

II. CONTEXT AND BACKGROUND

2.1. Circular economy in a broader context

Circular economy (CE) is a recently defined phenomenon for greening industries (Ari & Yilmaz, 2020). It aims to use Earth's natural resources efficiently and to decouple economic growth from environmental degradation (Scheepens, 2021). CE addresses decoupling, resource efficiency, production efficiency, slower material flows rather than linear economic models, and lower resource extraction without reducing economic activity (Mccarthy et al., 2018).

A CE is invigorating and recovering by design and targets to keep products, components, and materials at their highest utility and value at all times (Ari & Yilmaz, 2020). Durable design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling are identified as the ways to achieve a CE (Camilleri, 2018). New opportunities such as emerging sectors based on secondary material production remanufacturing, reducing risks on supply security from imported materials, and creating new decent jobs are identified as the major potential advantages of the circular economy practices (Mccarthy et al., 2018).

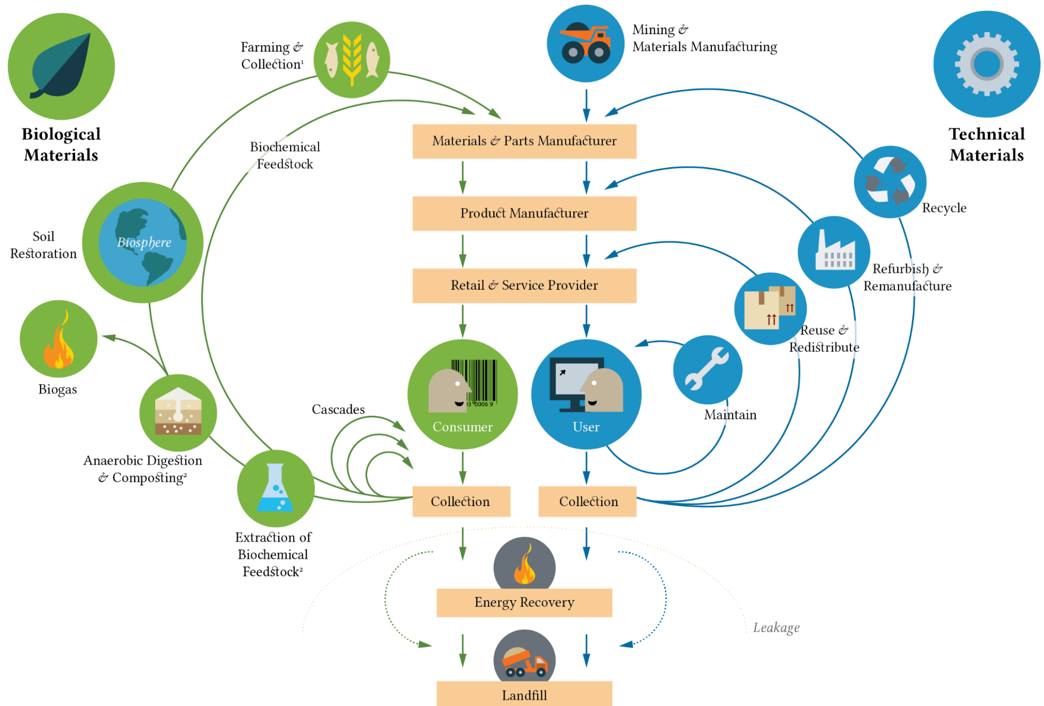

Figure: Circular Economy systems (Ellen MacArthur Foundation, 2019)

In a CE, material cycles are closed (Scheepens, 2021). By keeping products and materials 'in the loop', as in the figure, the CE aims to preserve resources. It can be done by extending product lifetime and recovering products, components and materials when they reach their end of operational life (Ellen MacArthur Foundation, 2013). This lifecycle perspective is central to the CE (Joustra et al., 2021).

2.2. Characteristics of wind turbine blades design

WTB integrate aerodynamic and structural design (Mishnaevsky et al., 2017). As in the figure below, shells on the leading edge, trailing edge, and the shear webs use a sandwich structure to provide high stiffness for minimum weight (Joustra et al., 2021). These shells are made of balsa or foam at the core and glass fibre-reinforced polymer (GFRP) surrounding them (Beauson et al., 2016). Spar caps introduce stiffness in the spanwise direction, i.e. over the length of the blade, to avoid collision with the tower (Scheepens, 2021). These spar caps mainly comprise GFRP. The shear webs link the two sides of the blade and also add stiffness (Mishnaevsky et al., 2017). These materials brought a high strength-to-weight ratio and rigidity to WTB (Jani et al., 2022) to withstand high wind speeds and be as light as possible to reach higher efficiencies (Scheepens, 2021).

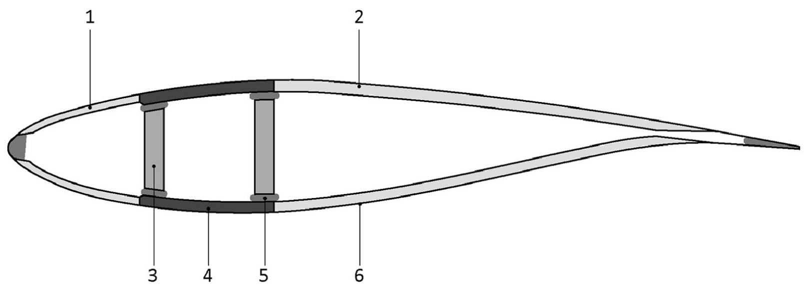

Figure: Cross-sectional profile of a wind turbine blade (Joustra et al., 2021)
1) leading edge, 2) trailing edge, 3) shear webs, 4) spar caps, 5) adhesive bonds, 6) coating
Source: [Structural reuse of wind turbine blades through segmentation - ScienceDirect]

With the growth in sizes, while predominantly made of GFRP, blades are reinforced with carbon fibre-reinforced polymer (CFRP), as carbon fibre (CF) has even higher stiffness and lower weight than GF (Beauson et al., 2016).

Design and certification guidelines stipulate a design life of 20 to 25 years (Germanischer Lloyd, 2010; WindEurope, 2017). However, decommissioning is often primarily an economic decision (Tazi et al., 2019). Measurements on a decommissioned blade showed that the material retained its original stiffness and strength (Beauson et al., 2016). It indicates that blades can still be in sound physical condition when decommissioned (Joustra et al., 2021).

2.3. Multiple circular strategies for WTB

In a recent report from the provinces of North Holland, South Holland, and Generation Energy, the circular strategies were determined for processing wind turbines based on the R-ladder, which indicates the degree of circularity. The higher a strategy is on the R-Ladder, the more efficient the strategy is, as in the figure below.

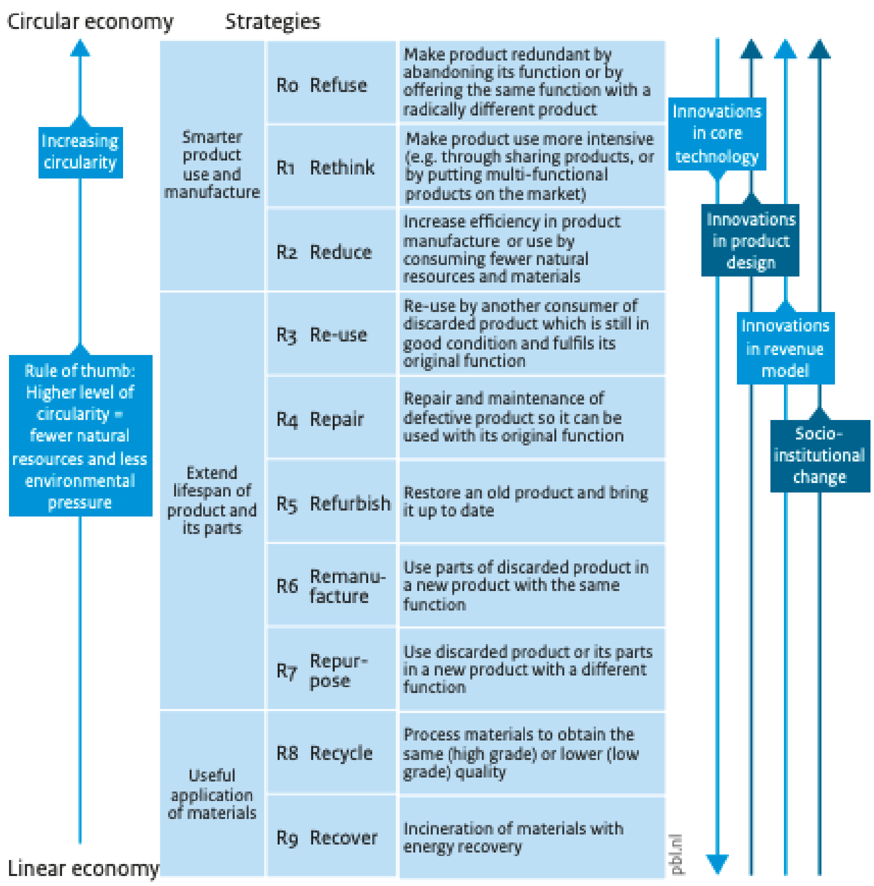

Figure: R-strategies

Source: [R-strategies / Circular facts | Smart Circular (slimcirculair.info)]

According to the report, R1-Refuse, Rethink and R2-Reduce strategies could not be adapted since the energy transition will be (partially) completed with generation by means of wind turbines. R3-Re-use, one of the most sustainable processing strategies, could no longer be applied due to short-term cost considerations of the product. R4-Repair is challenging to apply due to the permit period of WTB.

Replacing parts (R5-Refurbishing) is feasible to increase the yield of a turbine and could extend the useful life of the other parts. R6-Remanufacture is possible for small parts in turbines but is less common for parts with a significant space requirement, such as the blades because the cost of a new product is often lower.

R7-Repurpose has been developed in many ways. These range from sympathetic but low-impact repurposing (such as in playground equipment and skis) to speculative but with the potential for large-scale application (such as roof tiles, noise barriers and sheet piling). Other blade repurposing concepts are also shown in current publications, mostly in one-off applications, such as housing (Bank et al., 2018), and bridges (Jensen & Skelton, 2018; Speksnijder, 2018).

R8-Recycle, which processes EoL WTB into a new raw material through mechanical, thermal and chemical methods, is an option. However, the result has low quality and polluting, and energy-consuming processes are required to arrive at a new raw material. Data from the report shows that the turbine blade is heavily downcycled in the mechanical method, with the shredding and grinding process, and 40% of the material has to be disposed of as waste. The thermal and chemical methods, with pyrolysis and solvolysis processes, break down the material while the glass fibres remain intact. Consequences of these methods are residual heat and local nuisance from polluting substances. R9-Recover processes, such as incineration or noncircular processing, are undesirable and will be banned in the Netherlands, according to the report.

In the scope of the research, R7-Repurpose, with mechanical processes such as cutting and polishing, are required as practical techniques to transform EoL WTB into building elements.

2.4. A circular hub for end-of-life wind turbine blades

A circular hub as a treatment facility for EoL WTB has been suggested (Devic et al., 2018; Lobregt et al., 2021). It is the central community where a select group of stakeholders, from companies, NGOs, knowledge institutes, and governmental organisations, have collaborated towards a common goal: a circular wind industry (ECHT, 2022). The hub will also work as a platform to experiment and practise all circular strategies for EoL WTB. The research from Scheepens in 2021 expressed the urgency, feasibility, and potential value of developing a circular wind hub in the Netherlands. It presents that the circular wind hub would be located in a port. This solution would reduce logistics and storage costs (WindEurope, 2017). A port lends itself well to setting up such a hub: they are strategically located at sea, already has the infrastructure in place, and is already used for the installation and maintenance of offshore wind projects (Lobregt et al., 2021).

The research will be investigated further with a hypothesis that the circular wind hub, with the necessary facilities and mechanical techniques, has been developed in Eemshaven, one of four ports in the Netherlands that are used for installing and dismantling WTB.

2.5. Principle of building layers

The concept of building layers and their lifecycle was first introduced by Stewart Brand and Frank Duffy in 1994 and 1998, respectively. While Habraken in 1998 argued that the building only consists of structure and infill, Duffy and Brand believed that more time-related layers consisted. As in the figure below, they were shell, services, scenery and set as Duffy sees; and site, structure, skin, services space plan and stuff as Brand sees, where every layer has its own service life (Crowther, 1999).

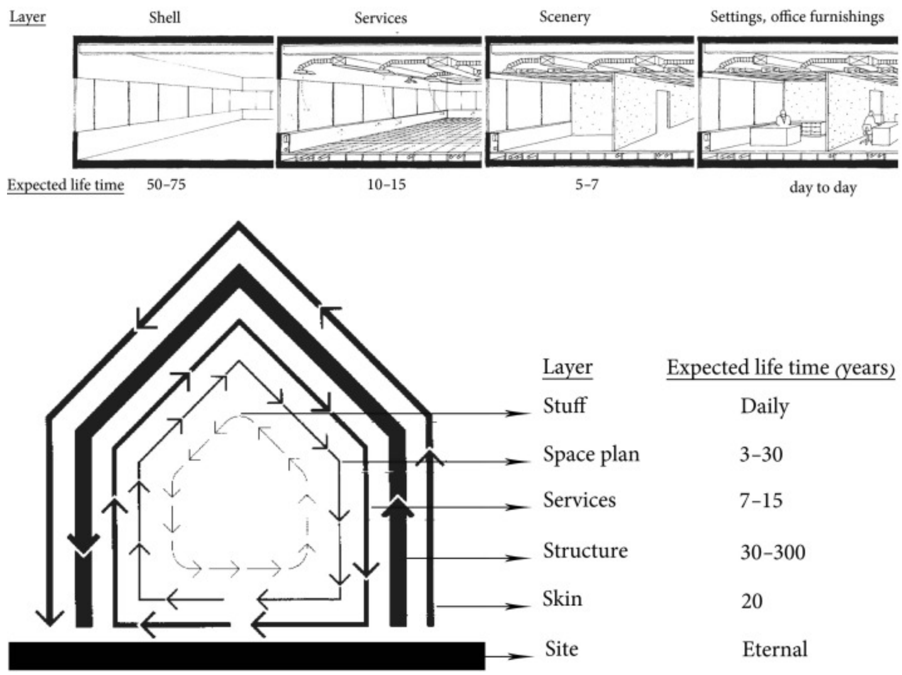

Figure: Building layers and their expected lifetime according to Duffy 1998, and Brand 1995, respectively
Source: [Durmisevic, 2010]

According to Duffy, the unit of his analysis is the use of the building through time; time is the essence of the real design problem. Because of different lifetimes, or different rates of change of building components, the building is constantly tearing itself apart, as Stewart Brand explained in his book, How Building Learn. These components and their lifetime are explained by Brand in table 1 below.

Building layer	Explanation from Brand
Site	The geographical setting, the urban location, and the legally defined lot, whose boundaries and context outlast generations of ephemeral buildings. It lasts eternally.
Structure	The foundation and load-bearing elements. These are perilous and expensive to change. Structural life ranges from 30 to 300 years.
Skin	Exterior surfaces change every 20 years due to trends, technology development, or for wholesale repair. The recent focus on energy costs has led to re-engineered air-tight and better-insulated skins.
Services	The working guts of a building, with communications wiring, electrical wiring, plumbing, sprinkler system, HVAC (heating, ventilating, and air conditioning), and moving parts like elevators and escalators. They wear out or become obsolete every 7 to 15 years.

Space plan	The interior layout includes walls, ceilings, floors, and doors. These can change every three years in commercial buildings. For quiet homes, they might wait 30 years.
Stuff	Furniture, phones, pictures, kitchen appliances, twitch around daily to monthly.

Table 1: Six S's - building layers and explanations according to Brand, 1994 (own table).

Recently, this principle has been developed by Superuse Studio as an expanded version. According to them, all layers, such as installations and other built-in parts, are separated so that maintenance is easy and future changes are possible. Extra layers, such as social and surrounding with their dynamic life spans, were included, as in the figure below.

Figure: Expanded version of building layers, according to Stewart Brand, 1995
Source: Superuse Studio

III. METHODS

3.1. Literature study (LS)

LS will play a key role in collecting data for the entire research. By LS, question (a) regarding the quantity of upcoming EoL WTB will be presented in sub-section 4.1. These quantitative data collected by LS will be inputs for Material Flow Analysis to investigate other questions.

3.2. Material flow analysis (MFA)

MFA is the primary method to answer sub-questions (b) and (c) about the outcomes made of Eo WTB and their lifetime with different circular strategies for EoL WTB, such as the quantity of the material and the amount of the product made after each circular strategy.

MFA is a method whereby a system-wide view is taken to track a material throughout its lifecycle (Allesch & Brunner, 2017). The mass balance rule is the underlying principle of an MFA; for example, every mass that comes into the system must also exit it or stay inside it as stocks. It delivers a complete and consistent set of information about all flows and stocks of a particular material within a system. Through balancing inputs and outputs, the flows of wastes and environmental loadings become visible, and their sources can be identified (Brunner & Rechberger, 2004).

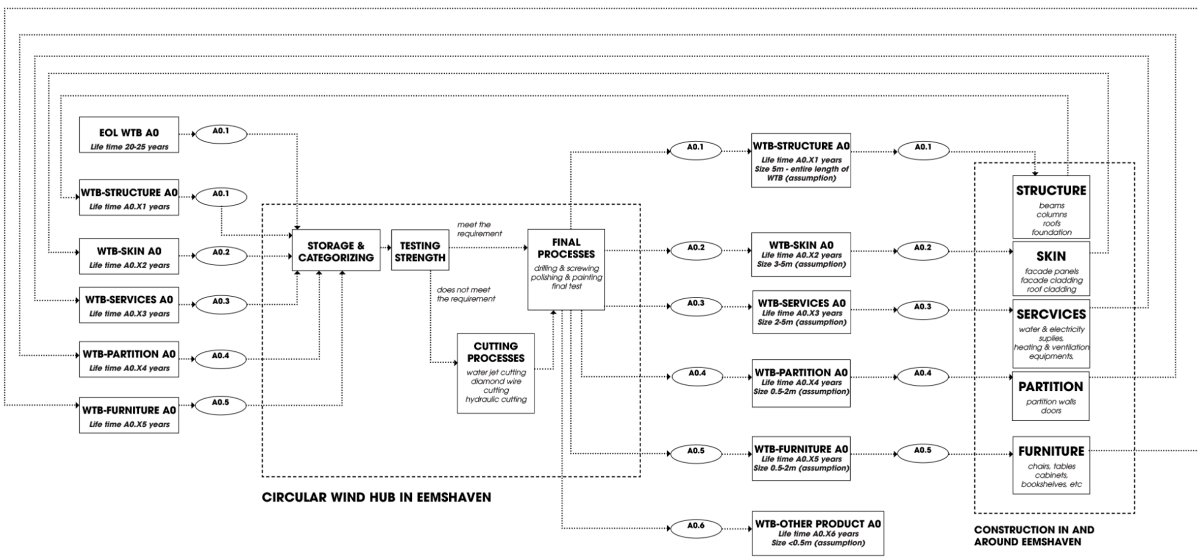

Figure: MFA of adapting EoL WTB to multiple building layers without lifetimes (own image)

This MFA illustrates the lifecycle of one type of blade after decommissioning. This material will be transferred to the circular wind hub and be transformed into multiple building parts through several processes, such as storing, categorising, testing, cutting (if applicable), and finalising. Outcomes from the that will be transported then work as building parts. After reaching the EoL of the new function in the building, these parts will turn back to the circular wind hub to be repurposed with the same process for the new use cycles. Several codes in the figure are explained as the following: A0: name of the blades; A0.X1, A0.X2, …: the potential lifetime of the building elements made of WTB; A0.1, A0.2, …: the amount of the blades or the building elements (tons, or pieces). Data related to the amount of building elements, such as A0.1 or A0.2, depends on the building design process and the user's demand; therefore, it will not belong to the scope of the research.

Although MFA remains a robust tool for assisting in policy discussions due to its potential to communicate general material trends effectively (Graedel, 2019), limitations of this method are uncertainties in the data used or missing data (Allesch & Brunner, 2015). This study approaches this drawback by including interviews to further investigate EoL WTB.

3.3. Interviews

Multiple interviews took place with experts in building construction and EoL WTB in and around the Netherlands. These aimed to determine qualitative data related to integrating EoL WTB in various building layers, including the structure, the skin, services, space plan and furniture. Each interviewee was selected based on their specific experiences in each building layer and EoL WTB, as in the table below. Due to the lack of reference practices and research related to adapting EoL WTB in the layer space plan or partitions, this layer was combined with the layer furniture as indoor elements. The structure layer required experience from various experts due to its complexity.

The order of various building layers made of EoL WTB, as below, was based on the order of each element's volume, from the largest to the smallest, through observation. This is also a strategy to treat EoL WTB in multiple-use cycles: from keeping the form of the blades entirely to shredding them into smaller parts.

Building's layers	Structure	Skin	Services	Space plan or Partitions	Stuff or furniture
Theoretical lifetime	30-300 years	20 years	7-15 years	3-30 years	5-15 years
Potential elements	- Frames (columns and beams) - Foundations - Roofs or Canopies	- Sun shading - Cladding	- Water system - Ventilation system - Heating system - Electricity system	- Walls - Doors	- Tables - Stools - Bookshelves
Experts	- Dr. Ir. Stijn Brancart - Ir. Hoessein Alkisaei - Ir. Sijke Prinsse - Arch. Jos de Krieger - Dr. Jelle Joustra	- Prof. Ir. Tillmann Klein	- Ir. Eric van den Ham	- Felix Tatantik	
Date(s) of interview	15th-23rd December 2022; 12th January 2023	13th December 2022	13th December 2022	19th December 2022	

Table 2: Multiple experts and their working fields related to different building layers and EoL WTB (own table)

These interviews will be semi-structured. That means a certain number of open-ended questions have been formulated in advance, and during the interview, there is room for new questions to arise from the ongoing dialogue (DiCicco-Bloom & Crabtree, 2006). Additional communications such as video calls and e-mail contact with experts from related fields will be conducted to get better data if MFA and other methods can not complete information.

Data from the interviews are separated into three main aspects of the building elements that are made of EoL WTB, including possibilities and potential lifetime. Other aspects related to the lifetime, such as structural calculation, maintenance, and building regulations, will be added based on the specification of each layer. All these aspects were formed by questions from the interviewer and the extra sharing of eight experts through open dialogues. The results of these interviews will fulfil the data in MFA (such as A0.X1, A0.X2) and will be shown in sub-section 4.2.

IV. RESULTS

4.1. Data of upcoming EoL WTB in and around Eemshaven

There have been nine large wind farms in and around Eemshaven, containing two offshore and seven onshore wind farms. As in table 2, With 150 turbines, Gemini is the largest wind farm, and N33 is the smallest, with 12 turbines. These turbines from Nordex, Enercon, Vestas, and Siemens have been operated since 2008.

Wind farm	**Area**	**Power (kW)**	**Number of turbines**	**Hub height (m)**	**Turbine manufacturer**	**Status**	**Commissioning year**
Delfzijl-Noord	Groningen	46,200	14	100	Nordex	Operational	2015/08
Delfzijl-Zuid	Groningen	32,000	14	85	Enercon	Operational	2008
GroWind	Groningen	54,000	18		Vestas	Operational	2008/07
N33	Groningen	64,500	15	135	Siemens-Gamesa	Operational	2020/11
N33	Groningen	51,600	12	135	Siemens-Gamesa	Operational	2020/11
Westereems	Groningen	105,000	35		Enercon	Operational	2009/08
Westereems	Groningen	108,300	34		Enercon	Operational	2009/08
Gemini	Offshore	300,000	75	90	Siemens	Operational	2016/09
Gemini	Offshore	300,000	75	90	Siemens	Operational	2016/07

Table 3: Operational wind farms in and around Eemshaven (own table)
Data source: www.thewindpower.net

From this data, a timeline of the upcoming EoL WTB in each wind farm has been made as presented in the figure below. The year of the decommission is based on the commission year of the blade and the approximately 20-25 years lifetime of WTB. In the upcoming period, 876 blades will be decommissioned from 2028 to 2045 in and around Eemshaven. Sizes of those blades vary from 35 metres to 68 metres. The largest blade waste is in the two Gemini wind farms, with 450 blades of 65 metres, which will come back to the land from 2036 to 2041.

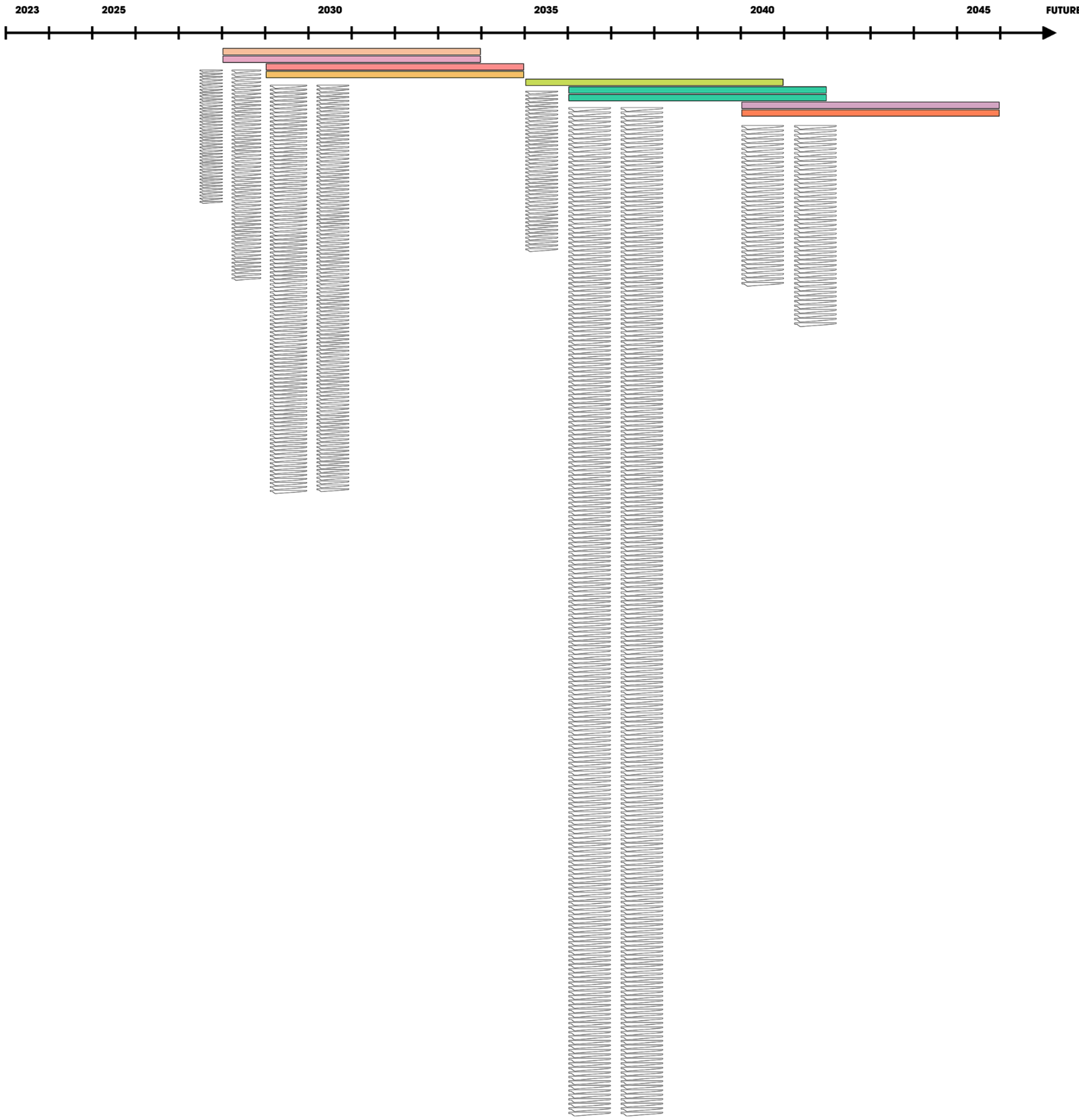

Figure: Upcoming decommissioned WTB in Eemshaven (own image)
Data source: www.thewindpower.net

4.2. Multiple building layers can be made of EoL WTB

4.2.1. Structure

4.2.1.a. Possibilities

From the interviews with four different engineers and architects, in general, for a structure, its material needs to have certain strengths. The strength determines its size. The weaker the material is, the bigger the structural component has to be. In this case, WTB has high strength and mechanical properties because they are used in these turbines, which usually deal with a lot of wind force. Different components of a WTB also have their own strength due to being made of a sandwich structure that's strong and stiff yet lightweight.

In application, it is possible when a blade is hanging on a turbine. In the structure, it is possible to hang it at one point and have it span for the length of the blade. The other point of the blade is the tip. When the tip becomes a part of the load-bearing structure, it is important to figure out how much it can hold and what happens if there is a dynamic load of people or snow on it.

Considering this material as a beam or a column, data from the interview shows that approximately 55% of WTB is eligible for structural reuse. The root and the tip of the element are the main challenges. The root is a plane cylinder with approximately 10 centimetres thick solid glass fibre laminate, which is difficult to process. The tip has a thinner laminate but is strongly curved or double-curved, making it less suitable for a direct reuse solution.

The blade’s tip always has curvatures, while normally, buildings are forced straight angular. It is less suitable for the structure. If a blade is used as a column or a beam, the tip needs to be cut or not be used as a structural part. Additionally, using the blade as the column is more potential than the beam. When putting force on the beam, the underneath is the tension part, and the upper part is the compression. While the column, it only has compressions.

Another consideration is using EoL WTB for a foundation due to the high-quality strength of the material. Normally, a pile of foundations, which are 40 or 50 metres long, often has a round or square or flat surface. WTB have a similar length, but the shape is pointy. If they are used vertically for the building’s foundation, they will go down when putting a load on them. An alternative solution is cutting the blade and removing the pointy element. If blades are used horizontally for the foundation, a calculation is still necessary to check their strength.

Cutting the blades will change its structural integrity from what it was before. It is required to be cautious about the number and positions of cuts for one blade and what will be achieved by doing that. An alternative solution is reusing the blade as a canopy. As findings from the interview, the moment of the structure will possibly work.

4.2.1.b. Potential lifetime

Although the lifetime of structures in the scheme of Brand and Duffy is 30-300 years, data from the interview shows that some previous structures last much longer. Churches were constructed hundreds of years ago. The Old Church in Delft, which has been used since 1350, is evidence. So the structure’s lifetime is possibly enhanced. Engineers know how to renovate the building structure to ensure it will last longer.

There is the structure as a whole and the structural components themselves. For the structure as a whole, adding beams will make it more stable; for one component of the structure, having more materials will ensure that if one of them gets broken, the whole structure is still fine. What often has been done with this is that they design the structure with over-dimension; the beam will be made to last longer than the requirement to ensure it is safe. So principally, having redundancy which is exactly too much, but it is better for the lifetime.

However, not similar to the church, using too many materials to make buildings last much longer is not a priority nowadays. The main requirement is a balance between designing a structure that can last very long and designing it efficiently.

Nowadays, building structures are demounted or demolished mostly because people do not need the building there anymore, not because the structure itself is not good. For the one made of EoL WTB, the users cut it due to their demands changes; even though structurally or mechanically, the structure is still good.

Despite the changes in demand, theoretically, it is possible to use the whole structure or parts of it multiple times to expand the lifetime. These typical blade structures will not last for 300 years. It is more of a temporary structure. It is the potential to take it apart and use three or four times for different functions. Then these structural blades can go up to ten years, and so on. In that way of reusing the structure, requirements are a range of well-defined use cases in various periods and the availability of mechanical processes on the local scale.

4.2.1.c. Maintenance

Maintaining the structure will help it work well, thus, increasing its lifetime. Each material has its own issues that require a specific way of maintaining. A full timber structure, including the connection, has an infestation of insects inside or becomes wet and dry many times and will degrade quickly. A steel structure has issues near salty water or an unexpected fire. Protecting their reinforcement from the water to avoid corroding is essential for concrete structures.

The structure made of WTB will not have those issues due to being designed for difficult situations, such as rains, storms, and cyclic loading. Protection of the indoor environment and stable loads will make the structure last longer than outdoor uses. Exceptions are applied for WTB that have Bansal wood as the core material. Exposing the Bansal wood to water will make it decompose and deteriorate. Therefore, keeping the existing blade form or taking proper protection for its cores will expand the lifetime. Additionally, the resin of the blade is not UV resistant. When exposed to UV radiation, the bear epoxy or bear polyester will discolour and disintegrate.

4.2.1.d. Building regulations

Up to now, there have been no regulations for building structures made of EoL WTB in the Netherlands yet. Normally, structures were designed and built for approximately 50 years, so they were usually calculated for that time. However, engineers have calculated with a bit higher effectors. If buildings were demounted after one year, this would mean that the chance of the building falling is less than when leaving them there for ten years. That is the philosophy behind the period of 50 years.

4.2.1.e. Structural calculation

Calculating a structure made of EoL WTB requires two inputs. They are a life cycle and fatigue analysis, which helps the engineer understand when these elements are safe and stable.

The fatigue analysis is based on the first life of the WTB. It was designed based on a certain amount of load cycles, which is how many times it rotates on the turbine. The degrading of the material is due to that dynamic situation. When the blade is inside a building, as a partition wall or as a column, there is no weather, wind, or dynamic force that would harm it. So 99% of the fatigue analysis is determined by the first life of a blade.

Even though the material is very durable, and we can improve its strength, the fatigue statics of the materials when it was on the turbine is a requirement. The interview finding shows that it took a long time to find an engineer willing and able to calculate this blade use.

4.2.2. Skin

4.2.2.a. Possibilities

Facades made of EoL WTB are feasible. They can be as sun shading or overlapping types of cladding. What needs to take into account is that the joints of different blades, or different parts of them, need to be taken into account because they have distinctive shapes. These joints have to be designed so that they can last very long without maintenance. All the details have to be used with stainless steel. If it is close to the sea, which has salty air, it has to be a good construction that does not rust away. Another notice is the surface of WTB. They were seen not too close since they were very high up on the turbine. If they are on the facade, coating them is necessary.

4.2.2.b. Potential lifetime

The number of years turbine blades will last as the building's facade is uncertain. It has been very long since, over time, they wear just by UV light and weather. Blades were made for dynamic loads. While in the building, there are not many dynamic loads like on the turbine. They are made for much more difficult situations than on the facade. Even if they are in the outdoor weather, they will not degrade. That material does not rot. They will last very long.

4.2.2.c. Building regulations

There are no precise regulations for the life span of facade elements in the Netherlands. There are only general restrictions on certain components that were believed how long they should last. Replacement is not necessary if they are still in good condition. For turbine blades, they are extremely strong and very sturdy elements.

4.2.2.d. Maintenance

The maintenance process is a matter of surface treatment. They need to be coated regularly. However, that would be more a matter of aesthetics rather than life extension.

Blades have white or coloured paint, similar to sailboats' surface. After a period, this surface appears chalky due to UV light.

Polishing and putting wax on is the maintenance for boats. This process has to be done once in a while with the WTB's surface. For a boat, the polishing job takes more effort than cleaning it. At least once a year, the boat needs a good polishing job and a new wax. For the facade, it will be longer.

The facade will not fall, but it becomes shabby after a while. Not maintaining it after five or ten years will cost much more effort than doing it in one or two years. Regular maintenance is more economical than doing it after a long time when the dirt is difficult to remove.

A noticeable part of WTB is the tip. Old wind turbines are not turning at such high speed, while the new ones, with much bigger blades, go at a very high speed. Due to this, there is more wear on the tip of the new big blade. Moreover, rain and hail also wear it. So every once in a while, they had to recoat the wingtips. When using them in a facade, this process needs to be continued.

4.2.3. Services/installation

4.2.3.a. The ventilation system

The blade itself is a big duct. It can be used as an air duct, usually aluminium or steel. Ducts come in different sizes, varying from one to ten centimetres in diameter. In a large theatre, they have a duct size of one meter.

Another potential is the air handling unit. It is a large box with a lot of components inside. Almost every building has this unit: housing, office, or industrial buildings. On the roof, these units have to be sheltered. The shell of the air handling unit has been made out of 40 centimetres to protect it from the environment. Normally, they are aluminium or metal boxes on top of the roof. Using each part of the WTB as an aesthetic cover. These shelters typically have a life cycle of 15 years.

4.2.3.b. The water system

The whole water system in the building, such as the pilot and the wastewater, is usually made out of PVC. In this system, there is rainwater storage, which is more common nowadays. Usually, these are black plastic tanks. They are possibly made out of EoL WTB.

From the interview, a rough calculation of the volume inside the wing was made based on its dimensions. On average, one square metre serves over the length of the blade. It will range from ten to forty cubic meters. So a small blade can contain ten cubic metres, and a big one will be thirty or forty cubic metres, which is useful for a storage tank.

It is possibly located above or partly above the ground. Besides the easy accessibility, it will be part of the landscape. It will be replaced or changed easily, compared with the underground tank. For maintenance, they often spray it inside after approximately ten years or more.

4.2.3.c. The electricity system

It is possible to make ducts with WTB by assembling them. Besides, electricity boxes can be made of this material. However, in the technical rooms, where not everyone can see, it is not for aesthetic reasons.

Related to the electricity system, but outside the building, the electrical box on the street is a potential option to adapt parts of the wing. What needs to be designed are various parts of the blades and their connections to assemble the box. Then it will be a piece of urban furniture made of EoL WTB instead of a plastic box. Their lifetime is 20-30 years.

4.2.3.d. The heating system:

The heating system is fairly standard, especially the radiators. They cannot be made of EoL WTB. For this system, using the material they often use is more sustainable.

4.2.4. Indoor elements (Furniture and Space plan / Partition)

4.2.4.a. Possibilities

From the interviews, multiple parts of WTB were moved into the home, the most extreme difference from the high-up outdoor place originally was, as multiple pieces of furniture.

This furniture series includes desks, coffee tables, stools, and bookshelves. The dimensions of each piece varied depending on the type of WTB used. The desk is approximately 280x90x75 centimetres (length x width x height), and the shelf is 215x332x45 centimetres. Due to their function, extra materials were added beside the WTB, such as a glass plate for the desk and a leather cushion for the stool. Each piece of WTB in each product was coloured with a layer of high gloss paint.

The challenge of this furniture is the manufacturing process. The finding from the interview shows that the blade's sturdiness from its original form and the build led to the designer aiming to impact the material as little as possible.

Further possibilities of EoL WTB in this scale are lamps and multiple outdoor furniture. These have been in the design process.

4.2.4.b. Potential lifetime

The lifetime of the product is the societal lifetime of usage. People or groups using that space need a replacement of their furniture after 20-30 years due to their new demands, not because the furniture or the objects are not usable. Being out of fashion is the reason that consumers end the lifetime of those pieces of furniture.

From the material point of view, the lifetime is endless. For stools, their leather cushions can last for 20-50 years. For bookcases or desks with glass and blades, it is much longer.

If the furniture comes to an end–of–life, it is updatable. With the rotor blade, keeping its original structure and form, or changing it as little as possible, will bring more possibilities. What has been done with these desks, shelves, and stools is sanding even pieces of the blade and colouring them with high gloss paint. Considering it as a bank account of possible changes, withdrawing only very little in the beginning will lead to many chances left for future updates. After 50 years, a table can be updated into something different.

4.2.4.c. Maintenance

Regarding the maintenance process, as with normal indoor furniture, wiping them down once in a while is necessary. For outdoor furniture exposed to the weather, they need to be cleaned at least once a year.

V. CONCLUSION

5.1. Analysis and interpretation of the results

5.1.1. Possibilities

Integrating EoL WTB into the aforementioned building layers is feasible, even though each layer has different requirements for specific parts where the material can be applied.

For the structure, data from the interview presented that approximately 55% of WTB is eligible for structural reuse. Beams and columns have potential based on outcomes from former research, while the foundations will need to be investigated more. Considering compressions and tensions, using it as a column is more recommended than as a beam. The root and the tip of the element are the main challenges of repurposing due to their forms with curvatures. Cutting the blade to detach them will change its structural integrity, thus, less recommended. Without cutting, an alternative use case for the blade is in canopies.

Calculating the structural quality of EoL WTB requires the fatigue static of the material when it was used on turbines. Due to the lack of this data, it will take a long time to figure out the precise calculation, according to different experts.

For the skin layer, decommissioned blades can be as sun shading or cladding. The joints of different blades, or different parts of them, need to be designed to work with different shapes and to last very long without maintenance. The surface of the material exposed to the UV light will need to be polished, cleaned or re-painted at least per 2 years for aesthetic reasons.

The services show that this material is adaptable in the ventilation system, such as air ducts in the building or handling units on the roof. Other applications are in the system of water, such as outdoor water tanks, and electricity, such as the electrical box on the street.

Multiple feasible applications of blades in furniture are lamps, desks, coffee tables, stools, and bookshelves. They only need to be wiped out once in a while like other normal pieces of furniture.

5.1.2. Potential lifetime

The structure made of EoL WTB can last 10-50 years. Ten years is the suggestion from the expert to test the material for temporary use. Because the fatigue statics of EoL WTB still need to be investigated, the precise structure quality is uncertain. So it is the potential to use them as temporary structures multiple times for different functions. This ten years period can be re-applied multiple times for different structural uses. Fifty years is the normal lifetime for the structure that engineers work with. Considering the fatigue static is available if WTB is used as a structure, its lifetime will need to meet 50 years as the requirement for other types of structure. Additionally, maintaining the structure will help increase its lifetime. So keeping the existing blade’s form and taking proper protection for its cores are a requirement from experts.

This lifetime for the skin elements is uncertain since the material can last very long. As on the facade, the component will not deal with many dynamic loads like it did on the turbine or on the structure. Even if they are in the outdoor weather, they will not degrade. Maintaining is necessary for the aesthetic of the material. Due to these strengths, the lifetime of this layer is endless. Since the structure has been considered a temporary use, the lifetime of the skin layer will be more than the maximum lifetime of structures, which is more than 50 years.

The lifetime of the services layer made of WTB depends on the system where the materials are applied. For the ventilation system, it is 15 years. This figure for the water and electricity system is ten years and 20-30 years, respectively.

The physical life of furniture will be 20-50 years due to the durability of the material and protection from the outdoor environment. Making the least adjustments with the material from the first process will lead to more possibilities to upgrade them and expand their lifespan after 50 years.

Data of 876 upcoming EoL WTB from sub-section 4.1, with their potentials and lifetime in multiple building layers that were investigated in sub-section 4.2, will be adapted to the MFA diagram at sub-section 3.2, as the image below:

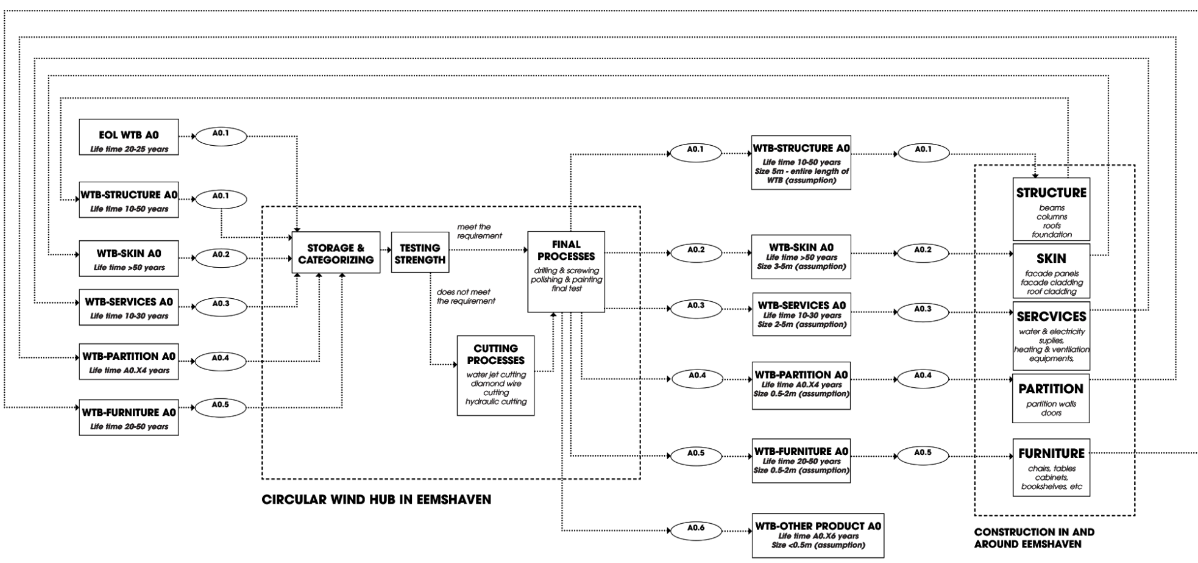

Figure: MFA of adapting EoL WTB to multiple building layers with added lifetimes (own image)

Combining those years from different layers above will present the lifecycle of EoL WTB that can be expanded by integrating them into buildings through multiple-use cycles (= A0.X1 + A0.X2 + A0.X3 + A0.X4 + A0.X5 + A0.X6). So after decommissioning, the material will last from 90 to 180 years. This number excludes the time of transporting or processing the material in the circular wind hub and the undefined lifetime of the space plan or partition (A0.X4) and other products (A0.X6). This is also the answer to the research question.

5.2. Discussion

The research investigates circular strategies for an end-of-life product and presents an adaptation for it to the building layers principle. It also contributes to establishing a Circular Economy for FRP components.

Generally, the research presented that integrating EoL WTB to various building layers through multiple life cycles is feasible. Results showed that the repurposing strategy could expand the lifetime of the composite component to 90-180 years, which is much longer than a decade, which is the period to separate resins from fibres on a large scale, as mentioned in section 1.1.1. In terms of CE, it can be considered an effective way to treat the large volume of waste and, at the same time, maximise its lifetime.

Repurposing through multiple-use cycles shows its potential to fulfil demands in the built environment while having less energy consumption and negative impacts on the environment, compared with other recent methods, such as recycling and repurposing on one-off applications.

Recently, design solutions with EoL WTB have gained criticism from the public that they might solve the problem of waste very little. An article from Jasper van Kuijk on De Volkskrant in 2022 about street furniture made of WTB could be an example. It is an opinion that EoL WTB should be tackled by a thermal or chemical process to separate resin and fibres at around 500 degrees Celsius, according to Harald van der Mijle Meijer in the same article. However, the progress will take at least one decade to do that on a large scale (Kroll, 2022), around 2032. Before that time, between 2028 and 2029, data from the research shows that in Eemshaven, 303 blades will be decommissioned. The length of each component is from 35 metres to 57 metres, which is similar to the average height of old churches in the Netherlands. If repurposing with existing mechanical processes is not applied, recycling will probably be the only available option. As aforementioned drawbacks of this method, it will lead to downgrading the material, heavy environmental pollution and energy consumption, which is not ideal due to the increasing energy cost recently. Therefore, compared to current recycling practices, repurposing or structural reuse requires relatively little reprocessing effort and, to a large extent, retains the material quality (Jensen & Skelton, 2018); it can be the most feasible option before an industrial scale of separating resin and fibres become feasible.

Regarding the structure quality of EoL WTB, the material's original design does not consider repurposing the material. This led to a lack of data for other applications, such as fatigue statics. Determining the degradation of material properties through fatigue and the extent of damage is challenging for composites (Nijssen, 2006). Insights from fatigue life prediction, structural health monitoring and damage inspection could improve the definition of post-use material properties (Joustra et al., 2021).

5.3. Appropriateness and limits of the method

This paper presented multiple potential outcomes of the waste material with data collected by MFA and interview experts. While other outcomes, such as skin, services and stuff or furniture, have shown their clear feasibility and quantitative data, outcomes for structure still need time to be determined more precisely regarding the recent strength of the material. It is due to a limited time for the research and a lack of fatigue statics of WTB. This can be a recommendation for further research in sub-section 5.5.

5.5. Recommendations

5.5.1. Recommendations to industry and policy

Generally, it is advisable for the industry to consider the following usage cycles while designing a product made out of waste or new materials. This can be established by including multiple-use cycles as design criteria. On a larger scale, multiple-use cycles can be included in regulation as a requirement for treating large volumes of waste.

Establishing repurpose pathway for EoL WTB in a Circular Economy required many stakeholders to collaborate (Joustra et al., 2021). As Kisi mentioned in research in 2021, a multi-stakeholder collaboration with different actors ensures the most effective transition to CE. Firstly, to facilitate repurposing EoL WTB into construction, new regulations from the government and related industries need to be developed.

Secondly, the upcoming design of WTB needs to take the repurposing process into account. The potential of this recovery strategy is acknowledged and has been demonstrated in occasional applications (Joustra et al., 2021). This can be done by creating a database for each WTB and tracking the flow of the component from the operation to decommissioning to the repurposing processes. This is in line with 'Buildings as Material Banks', which aims to integrate materials passports with reversible building design. This database of WTB should be public among the wind power and the construction industry. This collaboration is necessary for integrating changes, such as social, environmental, and economic impacts, in all stages of product life cycles (Brown et al., 2018). Then uncertain data such as fatigue statistics of the material will be able to be clarified.

Additionally, for 876 EoL WTB in and around Eemshaven will come back to the flow from 2028 to 2045, it is required for multiple stakeholders to find suitable demands in the built environment that can apply to repurpose WTB with multiple-use cycles.

In terms of circularity, the three most sustainable methods (R1-Refuse, R2-Reduce, and R3-Reuse) should be considered to integrate into the circular strategies for the wind power of Uitvoeringsprogramma Circulaire Maakindustrie. Even though transforming to renewable resources such as wind power is a priority, those methods are the fastest way to prevent the major waste volume in the future. This can be done by consuming less energy and focusing on only the most urgent needs.

5.5.2. Recommendations for further research

Further research could initially address the limitations mentioned in sub-section 5.3.

First of all, updating the research with new findings on the structural quality of EoL WTB is advised. An example was investigating fatigue statistics of the material when it was on the onshore or offshore turbines. This data will lead to a method to determine the structural ability of each blade component, thus recommending adaptable elements in buildings for that component. Another direction is elaborating the potential of the tip and root in the WTB. This will lead to the decision if the root and the tip need to be cut to repurpose the blade, or if it can remain in its existing form in a new function.

Another recommendation is to investigate the circular strategies for other types of waste through multiple-use cycles. The traditional way of designing, processing, or re-processing a product often transforms the materials or resources into a shape that serves the user's demands. In multiple-use cycles, this way might change to finding the demands that will fit the existing waste material shape, i.e. the EoL WTB. Fewer adjustments of the waste volume will cost less energy and pollution and create more opportunities to adapt it to further use cycles. This is in line with Circular Economy principles, which emphasise the importance of systems thinking and designing for multiple-use cycles (Ellen MacArthur Foundation, 2013).

Declaration of Competing Interest,

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

LITERATURE

1. Allesch, A. and Brunner, P.H. (2015) "Material Flow Analysis as a Decision Support Tool for Waste Management: A Literature Review," *Journal of Industrial Ecology*, 19(5), pp. 753–764. Available at: https://doi.org/10.1111/jiec.12354.

2. Allesch, A. and Brunner, P.H. (2016) "Material Flow Analysis as a Tool to improve Waste Management Systems: The Case of Austria," *Environmental Science &Amp; Technology*, 51(1), pp. 540–551. Available at: https://doi.org/10.1021/acs.est.6b04204.

3. Allwood, J.M. *et al.* (2011) "Material efficiency: A white paper," *Resources, Conservation and Recycling*, 55(3), pp. 362–381. Available at: https://doi.org/10.1016/j.resconrec.2010.11.002.

4. Ari, I. and Yikmaz, R.F. (2019) "Greening of industry in a resource- and environment-constrained world," *Handbook of Green Economics*, pp. 53–68. Available at: https://doi.org/10.1016/b978-0-12-816635-2.00004-3.

5. Bank, L. *et al.* (2018) "Concepts for Reusing Composite Materials from Decommissioned Wind Turbine Blades in Affordable Housing," *Recycling*, 3(1), p. 3. Available at: https://doi.org/10.3390/recycling3010003.

6. Beauson, J. *et al.* (eds) (2016) "MARE-WINT," *MARE-WINT: New Materials and Reliability in Offshore Wind Turbine Technology* [Preprint]. Available at: https://doi.org/10.1007/978-3-319-39095-6.

7. Boffey, D. (2021) *New EU target to cut carbon emissions by at least 55% disappoints experts*. Available at: https://www.theguardian.com/environment/2021/apr/21/new-eu-target-to-cut-carbon-emissions-by-at-least-55-disappoints-experts.

8. Brand, S. (1995) *How Buildings Learn: What Happens After They're Built*. Reprint. Penguin Books.

9. *Bridge of Blades – Stijn Speksnijder* (no date). Available at: https://www.stijnspeksnijder.com/gallery/bridge-of-blades/.

10. Brown, P., Bocken, N. and Balkenende, R. (2018) "Towards Understanding Collaboration Within Circular Business Models," *CSR, Sustainability, Ethics &Amp; Governance*, pp. 169–201. Available at: https://doi.org/10.1007/978-3-319-73503-0_9.

11. Brunner, P.H. and Rechberger, H. (2004) "Practical handbook of material flow analysis," *The International Journal of Life Cycle Assessment*, 9(5), pp. 337–338. Available at: https://doi.org/10.1007/bf02979426.

12. van Buren, N. *et al.* (2016) “Towards a Circular Economy: The Role of Dutch Logistics Industries and Governments,” *Sustainability*, 8(7), p. 647. Available at: https://doi.org/10.3390/su8070647.

13. Camilleri, M.A. (2018) *Closing the Loop for Resource Efficiency, Sustainable Consumption and Production: A Critical Review of the Circular Economy*. Available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3119575.

14. *CORDIS | European Commission* (no date). Available at: https://cordis.europa.eu/project/id/642384/reporting.

15. Crowther, P., 1999. Design for disassembly to extend service life and increase sustainability. *Durability of Building Materials and Components 8: Service Life and Asset Management*, pp.1983-1992.

16. Devic, A.-C., Ierides, M., Fernandez, V., Verbenkov, M., and Bax, L. (2018). Polymer Composites Circularity – White Paper. SusChem, Cefic, Bax & Company.

17. DiCicco-Bloom, B. and Crabtree, B.F. (2006) “The qualitative research interview,” *Medical Education*, 40(4), pp. 314–321. Available at: https://doi.org/10.1111/j.1365-2929.2006.02418.x.

18. ECHT (2022) *Report: how to facilitate the wind industry to become circular*. Available at: https://www.echt.community/report-how-to-facilitate-the-wind-industry-to-become-circular/.

19. Ellen MacArthur Foundation (2013) *Towards the circular economy Vol. 1: an economic and business rationale for an accelerated transition*. Available at: https://ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an.

20. Europe, W., 2017. Repowering and Lifetime Extension: Making the most of Europe’s wind energy resource. *The European Wind Industry’s Views on Managing Wind Energy Assets at the End of Their Operational Lifetime*.

21. Graedel, T.E. (2019) “Material Flow Analysis from Origin to Evolution,” *Environmental Science &Amp; Technology*, 53(21), pp. 12188–12196. Available at: https://doi.org/10.1021/acs.est.9b03413.

22. Jani, H.K. *et al.* (2022) “A brief review on recycling and reuse of wind turbine blade materials,” *Materials Today: Proceedings*, 62, pp. 7124–7130. Available at: https://doi.org/10.1016/j.matpr.2022.02.049.

23. Jensen, J.P. and Skelton, K. (2018a) “Wind turbine blade recycling: Experiences, challenges and possibilities in a circular economy,” *Renewable and Sustainable Energy Reviews*, 97, pp. 165–176. Available at: https://doi.org/10.1016/j.rser.2018.08.041.

24. Jensen, J.P. and Skelton, K. (2018b) “Wind turbine blade recycling: Experiences, challenges and possibilities in a circular economy,” *Renewable and Sustainable Energy Reviews*, 97, pp. 165–176. Available at: https://doi.org/10.1016/j.rser.2018.08.041.

25. Joustra, J., Flipsen, B. and Balkenende, R. (2021a) “Structural reuse of high end composite products: A design case study on wind turbine blades,” *Resources, Conservation and Recycling*, 167, p. 105393. Available at: https://doi.org/10.1016/j.resconrec.2020.105393.

26. Joustra, J., Flipsen, B. and Balkenende, R. (2021b) “Structural reuse of wind turbine blades through segmentation,” *Composites Part C: Open Access*, 5, p. 100137. Available at: https://doi.org/10.1016/j.jcomc.2021.100137.

27. Kişi, N. (2022) “The role of collaborative leadership in the circular economy,” *Circular Economy and Sustainability*, pp. 535–544. Available at: https://doi.org/10.1016/b978-0-12-819817-9.00011-9.

28. Larsen, K. (2009) “Recycling wind turbine blades,” *Renewable Energy Focus*, 9(7), pp. 70–73. Available at: https://doi.org/10.1016/s1755-0084(09)70045-6.

29. Liu, P. and Barlow, C.Y. (2017) “Wind turbine blade waste in 2050,” *Waste Management*, 62, pp. 229–240. Available at: https://doi.org/10.1016/j.wasman.2017.02.007.

30. Lobregt, M., Kamper, S., Besselink, J., Knol, E., and Coolen, E. (2021). *The ideation process focused on circular strategies in the wind industry*. ECHT

31. Lloyd, G., 2003. Rules and Guidelines IV, Industrial Services 1, Guideline for the Certification of Wind Turbines. *Germanischer Lloyd Industrial Services GmbH, Hamburg, Germany*.

32. Ministerie van Infrastructuur en Waterstaat (2023) *Klimaatbeleid*. Available at: https://www.rijksoverheid.nl/onderwerpen/klimaatverandering/klimaatbeleid.

33. Mishnaevsky, L. *et al.* (2017) “Materials for Wind Turbine Blades: An Overview,” *Materials*, 10(11), p. 1285. Available at: https://doi.org/10.3390/ma10111285.

34. Nijssen, R.P.L. (2006) *Fatigue Life Prediction and Strength Degradation of Wind Turbine Rotor Blade Composites*. Available at: https://energy.sandia.gov/wp-content/gallery/uploads/SAND-2006-7810p.pdf.

35. Offshore Renewable Energy *et al.* (no date) *Sustainable decommissioning: wind turbine blade recycling*. Available at: https://ore.catapult.org.uk/wp-content/uploads/2021/03/CORE_Full_Blade_Report_March_2021-FINAL-4.pdf.

36. Oliveux, G., O. Dandy, L. and A. Leeke, G. (2015) *Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting properties*. Available at: https://doi.org/10.1016/j.pmatsci.2015.01.004.

37. *Ontwikkeld voor een andere toekomst* (2022). Available at: https://www.groene.nl/artikel/ontwikkeld-voor-een-andere-toekomst?utm_campaign=website.

38. Pronk, S. (2022) *Repurposing wind turbine blades as a construction material | TU Delft Repositories*. Available at: https://repository.tudelft.nl/islandora/object/uuid:d06683eb-3e99-44f7-992c-2040572301cb?collection=education.

39. Royal Haskoning DHV (2018) *Fiber Reinforced Polymers (FRP) in infrastructure*. Available at: https://vdocuments.mx/fiber-reinforced-polymers-frp-in-infrastructure-tromp-rh-fiber-reinforced.html?page=1.

40. *Ruimte voor circulaire windturbines* (2022). Available at: https://circulairemaakindustrie.nl/documenten/ruimte-voor-circulaire-windturbines/.

41. Saidi, T., Hasan, M., Amalia, Z. and Iqbal, M., 2022. Behaviour analysis of strengthened-RC beam with natural fiber reinforced polymer (NFRP) based on abaca fiber by using finite element method. *Aceh Int. J. Sci. Technol*, *11*, pp.155-164.

42. Salama, W. (2017) “Design of concrete buildings for disassembly: An explorative review,” *International Journal of Sustainable Built Environment*, 6(2), pp. 617–635. Available at: https://doi.org/10.1016/j.ijsbe.2017.03.005.

43. Scheepens, W. (2021) *A circular hub for end-of-life wind turbine blades | TU Delft Repositories*. Available at: https://repository.tudelft.nl/islandora/object/uuid:58499aba-f7ae-494c-aea6-4465669b06dc?collection=education.

44. Schmid, M. *et al.* (2020) *Accelerating Wind Turbine Blade Circularity*. Available at: https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Accelerating-wind-turbine-blade-circularity.pdf.

45. Superuse Studios (2021) *Shearing Layers*. Available at: https://www.superuse-studios.com/about-us/.

46. Tazi, N. *et al.* (2019) “Waste and material flow analysis in the end-of-life wind energy system,” *Resources, Conservation and Recycling*, 145, pp. 199–207. Available at: https://doi.org/10.1016/j.resconrec.2019.02.039.

47. “The Macroeconomics of the Circular Economy Transition” (2018) *OECD Environment Working Papers* [Preprint]. Available at: https://doi.org/10.1787/af983f9a-en.

48. Tromp, L. *et al.* (2016) *Prospect for new guidance in the design of FRP*. Available at: https://eurocodes.jrc.ec.europa.eu/sites/default/files/2021-12/ReqNo_JRC99714_lbna27666enn.pdf.

49. T. H. van der Meulen *et al.* (2020) *Offshore windpark decommissioning*. Available at: https://pure.tudelft.nl/ws/portalfiles/portal/102624565/Offshore_windpark_decommissioning_report_SmartPort_TNO_TU_Delft.pdf.

50. van Weezel, T.G. (2022) *Nieuwe productiemethode maakt rotorbladen van windmolens goed recyclebaar*. Available at: https://www.volkskrant.nl/nieuws-achtergrond/nieuwe-productiemethode-maakt-rotorbladen-van-windmolens-goed-recyclebaar~b36025207/.

51. WindEurope, Cefic, and European Composites Industry Association (2017) *Accelerating Wind Turbine Blade Circularity*. Available at: https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Accelerating-wind-turbine-blade-circularity.pdf.

52. Yang, Y. *et al.* (2012) “Recycling of composite materials,” *Chemical Engineering and Processing: Process Intensification*, 51, pp. 53–68. Available at: https://doi.org/10.1016/j.cep.2011.09.007.

53. Yuan, Z., Bi, J. and Moriguichi, Y. (2008) “The Circular Economy: A New Development Strategy in China,” *Journal of Industrial Ecology*, 10(1–2), pp. 4–8. Available at: https://doi.org/10.1162/108819806775545321.

APPENDIX

Interviews

Interview Stijn Brancart

Stijn Brancart, an Assistant professor of structural design at Delft University of Technologies (TU Delft). Obtaining an MSc in Architectural Engineering from the Vrije Universiteit Brussel (VUB) in Brussels, Belgium, in 2018, his work focuses on the design and analysis of flexible and responsive systems and circular structural design. At the moment, Brancart is teaching various courses on structural design and analysis in the Technology track of the BSc in Architecture as a member of the Department of Architectural Engineering & Technology.

In my research, the lifetime of the building's structure made of wind turbine blades is the main focus. Theoretically, it will last from 30 to 300 years, according to the scheme of Brand. How can this be seen from your experiences?

The lifetime of the structure, as here in the scheme, is the most important thing. Between 30-300 years is really wide, and it is very different compared with the lifespan of other elements. It is due to different aspects. In use, the structure part lasts longer than the other. In terms of maintenance, I think it is important to consider as well as potentially there, because maintaining the structure well will also increase its lifetime. The idea here is that you develop a scheme that shows them when to decide to take it out then the structure life can last longer.

So here it is 30-300 years, but that are also previous structures that last for much longer as well. For instance, churches here are still in use after hundreds of years. There are a couple of elements there. So one is that usually in the building that lasts so long, but they are also over the dimension. Its big wall can last hundreds of years. That's the double thing because you don't want to use too many materials like that. It is a beautiful balance between designing something that can last very long and designing something efficient.

What I think is interesting here, I don't know how far you can go, is that you design a structure, but it can also even adapted or improved in the future. So you say where you can easily replace elements. It looks a bit more difficult to use the whole blade as one. What you can do is divide it into little ones.

Using the existing shape of the blade to design should be the first option due to keeping the original quality of the product. What I am wondering now is if the existing blade is strong enough for the structure.

I think it will be strong. Now building structures are demolished quite differently. Actually, mainly it is due to you don't need the building there anymore. In many cases, it is not the structure itself that is not good. Because we actually know how to renovate the building structure to make sure it will last longer.

As for the monument, we never tear it down. Once we decide to include it in the future, we just keep it working.

Theoretically, something that you can improve can be parts of the structure or parts of multiple structures. Because for these typical blade structures, you will not have it for 300 years. Here it is more of a temporary structure. Then you can take it apart and use it 3 or 4 times for different functions, and it is still okay.

You can evenly go from this structure. For example, if you take apart the element, I think that would be valuable, then you can really go up to 10 years for this structure and so on. I do not know about the original material of the blade completely, but I see we are not really talking about making a structure that will last hundreds of years. The only question is will you keep finding different functions for the structure in the next periods? Even when you find them, I can imagine at some points; people say they want to cut it to use it for something else because they do not need it as the structure anymore. Maybe structurally or mechanically, it is still good.

So will there also be a potential to reuse the blade as a structure after the structure period if it is still in good condition?

If we talk about reusing the structure, then what often happens now, as in your diagram, is that you are not always sure when you can get the component. And you also do not want to assume that it works really well if you are not really sure. What often has been done with this is that they designed it with over-dimension; they use the beam that actually lasts longer than the requirement to make sure that it is safe, like this. So I imagine you do not have to think about that when you use them very efficiently, you use the same wind turbine for this span. And then, in the second step, you use it for a smaller span.

One reference for this material is research from the faculty of Civil Engineering at TU Delft. Simon Pronk, a Master's student from there, has used these parts of blades as an I beam for the structure.

That’s interesting because you can have two I beams, for example, one big and one other smaller. He would leave some more over-dimension anyway, but I think it is fine it's not using really more materials.

I am not sure something like he did, is a good option. The blade should be designed with the existing shape of the material instead of forcing or transforming it into something we want.

Yes, true, it could be. Think about structure; for example, you could see this as a canopy, something like this. Then the bending moment will go like that. Then you will have more moments in here than in here. So you can imagine that you will use it like that.

Relating to a canopy, a 747 wing house in America is a good reference to look at.

Very interesting. This part will be much lighter here, and you have a bending moment here… You have a reference already so you can use it. You have the shape and the ability already. You need to design it in an efficient way.

If it costs a long time to investigate the structural ability of these blades as beams, do you think using them as columns or a roof like this has more potential?

It could also work. It could be a very good grid. So as a roof, it has to be something very strong which it can be to handle the load.

How did we work with the lifetime of the structure that was made of other materials normally?

That is a good question. Regarding the structure, it is not straightforward. For other parts, they are more about design. For structures, it's really quite open. There are different things: the structure as a whole and the components themselves. The structure as a whole is often; the question is how long it can stand in extreme situations. The solution is adding as many elements as you need. For example, you have a structure as a whole; then you add beams to make it more stable. It is different when you have one blade for the structure, but sometimes it is better to have a couple or more of the material to make sure that if one of them gets broken, the building as the whole structure is still fine. So you have redundancy which is exactly too much, but it is better because you can extend the lifetime.

But it is not only about that. The other thing is that there are different ways of maintaining. They often said that buildings that are made of timber structures last less long than ones made of concrete or steel. For example, the full timber structure, including the connection, can stand there for hundreds of years. So it is not that simple to say it is mainly due to the material. It is about different ways of maintaining the construction. When you have an infestation of insects in it or when it becomes wet and dry, and wet and dry again, it is very bad for the timber. It will be degrading very quickly. It is really about maintaining it well. Steel also has some issues but with a different context. For example, near salty water or something, it can corrode easily. When there was an unexpected fire in a building, then the material would also get worse. In concrete, the problem is quite different. It is more about how you protected the reinforcement. If the water comes in, the steel will corrode, and it will affect the concrete terribly. So it depends a bit on the material. What you have to do is avoid those problems to make sure that the material will last longer.

How about the structure with wind turbine blades? What can be the challenges of it, and how long can it last?

The benefit you have here is that the wind turbine blade does not have those issues of the other materials. It was designed for the outside environment, against rain, strong wind, and storms. Also, cyclic loading. For example, cyclic loading is when you load something on top of it occasionally. You load it heavily, unload it, and then do it again. These blades have been made with dynamic loads. When they are put inside the building, they have more protection, and you have a stable load as in the building structure instead of the cyclic one in the turbine. So it will be quite fine.

It is difficult to put a number on it without calculating. Like other structures, it is very important. Because it is not just about whether it is looking fine or performing fine. When it does not perform anymore, it will be dangerous. So it has always been designed with more caution.

Principally you need to maintain these blades well as a structure and make sure that they work in the most optimal situation. Then we can extend their life really, really long.

It is nice to think about this specific material. Looking at the performance of this in the previous function, maybe, or how long it has performed before, what are the optimal conditions for it to last a long time?

From Neowa last year, there are only 2 of them were destroyed by the thunder, among hundreds of blades.

Okay, that is an important thing to know about this material. That situation has never happened with buildings. We can see all the most popular dangers for other structures, such as timber, steel, and concrete; they are not happening with wind turbine blades.

It will cost time for the engineer to calculate it. Double-difficulty, one is that it does not have a familiar geometry that we used to work with, and also, it is an existing component which we hardly know precisely the recent quality of it. Even though the material is very durable and we can improve it by somehow making it super strong, we do not know the fatigue statics of the materials when it was used on the turbine.

But I think the worst thing that can happen there is you can use it with more caution. When using the component that could be used for higher loads or lower loads for over-dimension. But it is more for the structural solution than architectural tasks.

Do you see the lifetime of 50 years of the timber structure can be adapted for a simple structure with wind turbine blades?

Usually, building structures were designed for at least 60 years. In many timber buildings, it even lasts much longer. I think it depends on which kind of timber structure they use or different types of wood (hardwood or softwood). Then after a period, the timber engineer cannot assume if the glue of the timber still works.

For the lifetime of the structure made of wind turbine blades, I would not be too hung up on certain numbers, like 30-300 years. It can be even much longer than that. But I would say it is between so much and so much. So you can have some scenarios for these structures. One scenario is you have 25 years, but I would not conclude that it is only 25 years. After 25 years, if it is still good, it can last much longer.

So when you make a plan for future blades, people can change it anyway based on their demands. Maybe after 5 years, they do not need the structure anymore even though they know that it is still good for 20 more years.

And they need to have a certain period to test the structure, at least 5 years, for example, for a temporary function such as a pavilion or a greenhouse. Then they will know if it is still good to keep using it as the structure or if they should use it for other elements as other functions.

Interview Silke Prinsse

Relating to the structural ability of the WTB, another interviewee is Silke Prinsse. Besides working as a professional structural engineer since 2018, Prinsse has been a tutor in the Structural Design & Mechanics Group at TU Delft's Department of Architectural Engineering and Technology since 2021.

At the moment, the main process for end-of-life wind turbine blades is transforming them into tiny pieces and using them as a replacement for sand in producing cement, which will be used for making concrete later on. What is your opinion about this?

Others have mentioned that this process is more about downcycling than recycling. So normally, you have concrete, and then you have reinforcements. We use concrete that has been used every year. But if you're changing the ingredients, for example, minerals, the chemistry of the process changes, and it will interact with the reinforcement steel. That is also sort of a new thing. But without researching what it is, you know, it changes the whole process, including the mechanical properties or the lifespan. So maybe, in 50 years, it will have a process that we don't know yet.

Compared with normal construction, what is the potential of using these blades as a structure?

One important thing is that blades always have curvature, for sure. There's always a curvature in the blade, while normally, many buildings are forced straight angular. If you would use part of it, for instance, you cut this part and look from the side, that's not completely straight. I think that's one of the main differences. So you always have a strong sort of curvature that you need to design with them. For a facade, it could still work, but it maybe has some influence on how you detail it because you have this slight curvature. And I think it also depends on the part of the blade where the curvature is the most. At the end parts, curvatures like this may be less suitable. But the in-between part might be more suitable.

I'm just curious about all these blades, they're circular in one direction, and then they always have tension at one side and compression at the other side. For instance, you have compression on this side if it's bending and compare and tension on the other side. Both sides have the same amount of glass fibres and resin; they just vary the thickness. I am not sure, but it could also be engineered material in places where they need more strength.

What is the potential lifetime of this structure? Or how can we estimate it?

It depends on if you put it inside or outside. The turbines rotate all the time. So it's a very dynamic structure. The blades are designed for fatigue. It is like a dynamic process; if a certain thing has a certain strength put on it, this is the case it is rotating all the time. The material becomes weaker at a certain point. This is not the case in a static environment. They designed the material based on a certain amount of load cycles. For instance, this thing should be there for 30 years; how many times is it rotating at an average wind speed? So the materials degrade because of the number of cycles.

That is very different when you would put it in a building, and you have a column there, then you just have a permanent load on it, and nothing is changing.

The degrading of the material, I would say many problems for it in a dynamic situation. When you have an old blade which is at the end of its lifetime, what is the strength still? That is one of the problems or difficulties in determining.

So if I understand correctly, the main factor that affects this material is the weather condition, right?

I would say the most extreme situation it already had is the rotating thing, and when you're just using it as a partition wall or as a column inside, there's no weather, no wind, or dynamic force that would harm. I would say 99% of it is determined by the first life as a blade, which has been there for 20-25 years.

Besides the beams and columns, how about other structural elements?

It would also function as a facade material. The only thing is that you need to detail it properly. I can imagine it's easiest to use it as a roof because it's such a big thing. So if you use it as a column or a beam, the end part needs to be cut or not be used as a structure.

For some buildings that have been demounted after a certain period, is that mainly due to the materials?

I would say the lifetime is probably not dependent on the material but on the use of the building. If there's a building that is being demounted after 30 years, then that's the end of it, not the end of the materials. For the materials, if you use it as columns or beams, it's not gonna degrade like it're doing as a wind turbine. I think it's determined by other restraints, like the whole surroundings and the building.

In the Netherlands, how is the structure calculated normally?

In the Netherlands, for structural engineering, we design and normally built for approximately 50 years. When you're designing buildings, you have a lot of factors between the real load and the load you calculate. Because you want some safety, and the safety factors are based on all statistics, such as how many casualties we accept for a year. It also depends on how long is the life span of the building. So we usually calculate for 50 years. But if you, for instance, calculate for 100 years, you would calculate with a bit higher effectors. That's the philosophy behind calculating structure for buildings.

Of course, when you calculate something, you need some kind of thinking about how many years it will last. That's the whole philosophy of safety. The average span of a building is 50 years, then it would be calculated based on that. If every building would be demounted after one year, then this would mean that the chance of the building falling down is less than when you left it there for 10 years. So that's what I mean; the philosophy is based on 50 years. That's what I generally do.

What are the challenges of calculating structures made of wind turbine blades?

Usually, in the calculations, we look at two things. The first is strength, we accept a material should be strong enough. The other thing is deflection. It is a very strong material, and it is deflecting a lot. You could imagine you can walk on a cloud thing. You put a lot of tension and force into it then you have the feeling you're falling. That is for the beam or the floor.

What is easier with the column than the beam is that: If you have a force on the beam, then it's going to bend. The underneath of the beam will be the tension part, and the upper part is compression. With a column, it is a bit different because you have a force on it, and then you have actually compression in it. You actually only have compression.

Could you share the relation between the volume and the strength of the structure?

For structure, the material needs to have certain strengths. When its strength is low, that's okay; we can design it as a bigger component. But when it's super strong or whatever, then we can make it. The strength of the material determines its size. The blades it's very strong, or at least strong enough because it was used in these turbines, which often deal with a lot of wind force.

Interview Hoessein Alkisaei

Hoessein Alkisaei works as an engineer and a project leader at Engineers Without Borders, along with running his own firm Nederland Maakt Impact. Since 2020, Alkisaei has been teaching structural and building engineering at TU Delft. He is the main tutor of Simon Pronk, who did research about repurposing WTB as a construction material in 2022.

Could you share about experiences with wind turbine blades as the construction material that you and Simon Pronk gained from his previous research?

The material is super strong. But it also depends on the way you design it. If the load is way stronger than the structure, the lifetime is probably one day. So you have to figure out and really understand, like, okay, what am I going to use these elements for? What is the application? What are the load forces that are acting on these materials? And how much can these materials and structural elements take these loads? And after what time is the element not applicable anymore?

Normally, how do we calculate the strength of a structure?

The first thing you need to figure out is the life cycle analysis. That is the famous lease, the LCA. And the second thing is a fatigue analysis. So basically, these two things. In addition, you can also do an Ultimate state - Limit State and Serviceability - Limit State. These are also two analyses in which you also use the loads in the materials to understand how much and when these elements are safe and stable used. So the characteristics of the materials are the important thing to analyze, yeah.

What tools did we often use to do that?

We often use a lot of software, and there is one called Dianna, and there is one called Matrix frame. Yeah. These are well. You can also try on these, but I see also nowadays they are in using Grasshopper. Also, Grasshopper is not per se the best way to go. But yeah, you can try to see if there are packages in grasshopper that can do it. But I think maybe the easiest is Matrix frame because it is in 2D, and it already has regulations in it and other data.

What is its potential lifetime of it? Especially in this case, the structure is made of wind turbine blades.

Well, for instance, like a bridge, the materials in it can stay for 100 or 50 years. However, in buildings, they can stay for 200 years. It not only depends on the application of the material but also very much depends on the environment. So like a bridge, its structure is mainly outside, while in the building, it is inside and hence, is more protected. So that is why the lifetime differs per application, even though they have the same material. For instance, concrete and concrete, but because of the application and the environment, the lifetime is very different. So that is why when you start thinking about using these blades inside or outside, will lead to a big difference. That is why you should look at how this material is affected by the environment, which means the weather, loads, and people with the foundation. It will cost time to calculate that.

Mentioning the foundation, is using wind turbine blades also a possibility?

The problem is the shape of it because it is like quite pointy. So when you put a load on it so might it might go down because it's sharp, though. So in this shape, it is, yeah, I need to do some calculations; otherwise, it is going to be very hard.

It is a long shot for elements. A pile or foundations are like 40 or 50 meters long, of course. But these pile foundations are like, for instance, round or square or flat surfaces. But the problem is that the blade is pointy. It is like a needle, and when you push a needle somewhere inside, it will go deeper, deeper, and deeper. That this is the problem at the moment with the blades. So if you want to use blades as Foundation or you put them horizontally, then you need to calculate it to check if it is horizontally strong enough. Or you need to cut the blade somehow until you have until you remove this pointy element of the blade.

Interview Jos De Krieger

Jos De Krieger is an architect and the founder of Blade-Made, a collaboration between the sustainable Rotterdam architectural collective Superuse Studios and a number of foreign partners. Since the creation of the first playground made of decommissioned WTB in 2009, he has been involved in a number of other projects in the Netherlands involving similar materials.

Having years of working with end-of-life wind turbine blades, could you share the vision of you and your firm about this material in the future?

Well, I would say the vision for Blade-Made is that we want to inventory and categorize all blades that are coming away in the next decades and give them a functional second life before they reach their end of life. So, we should know in advance what is going where. And if that means that everything can be playgrounds, that is fine. However, that is probably not realistic. And that's why we are looking at the sound barrier as one of the main solutions for the large flow of material. Because this is a relatively easy way to make functional storage of the material and keep clear control of all the materials for future recycling opportunities. So if the sound barrier becomes a necessity or end-of-life, after 25 or 50, or even more years, all the material will still be together instead of distributed throughout the whole urban environment.

What are the opportunities and challenges when working with end-of-life wind turbine blades as a structure?

Well, in general, my experience is that the material is really strong and especially when it is in a context where it is sort of out of reach because everything can be destroyed. That's why we also have the possibility to recycle it or downcycle it by breaking it into pieces. I do not know about its structural uses in buildings. However, just like any other column or beam, there is an opportunity to break it either by force or fire or by something else. They are something that I'm not worried about, or at least not hesitant to look for architectural solutions. Although I do find it interesting to see what's possible.

Could you share your experience with the bridge project, which was designed with end-of-life wind turbine blades?

Well, the bridge was not my project, so I do not know all the details, but I know that it took quite a while to find an engineer that was willing and able to calculate this use of the blade. And finally, we found someone from cement or at least from a wind turbine manufacturer. He was able to make the translation from blade to bridge in his calculations. Because for a traditional engineer, it might have been too challenging or out of the standard solutions. So it is basically you need an inventor kind of engineer willing to come up with ways to prove something that has not been done before. That is always tricky but also interesting.

Principles of using wind turbine blades as a structure?

Well, basically, there are some simple things that you already know. For example, if the blade is hanging on a turbine, that is possible. So it is possible to hang it at one point and have it span for the length of the blade. The problem is when you start to put the way this region, also, on the other end. So, the tip is becoming part of the load-bearing structure. How much can that hold, and what happens when you have a dynamic load of people or snow or other things that stay on the blade? What will that mean?

What is the lifetime of wind turbine blades as a structure?

Since what the other experts already said is that the lifespan of the materials basically forever. So it depends on the application that you make and what the actual life span will be. And if you apply it in such a way that it is out of reach, then you could say that it is forever. So it depends if it becomes columns or beams or if it's cut up into small pieces and this rigid everywhere. I think that every cut, in general, will make the material weaker. Because you are always changing the structural integrity of what it was before. That is something to be at least cautious or careful about in how many cuts you want to make, where you make them, and what you want to achieve by doing that.

And the other thing is, basically, most of the blades are high profile, or what do you call it: a square profile, with an addition of a front and a back…

Interview Jelle Joustra

Jelle Joustra presently working on his PhD at Circular Product Design, in the department of Design Engineering at TU Delft. His research is a component of the Ecobulk Horizon2020 project, which brings together partners from business and academics to close the resource loop for composite materials. The End-of-Life scenarios for wind turbine blades and the design assessment of items for the building, furniture, and automobile industries are the subject of his current research.

Having years of working with end-of-life wind turbine blades, could you share a brief of your progress?

Well, I split the publications of that into two publications. But basically, it was one big project where I aimed to segment a large blade into reusable panels and then use those panels in subsequent products, like simple furniture and construction products.

I did a couple of studies, one of which was reusing or repurposing blades as load-carrying beams in a bridge. We found that an interesting application, but I also realised that that probably would lead to the need to design each bridge based on the available materials and based on the available location. And as such, it will not lead to a large volume of blades being reused because of the relatively high effort.

First, the volumes of blades being involved. given a large number of blades or a large number of wind turbines that will be decommissioned, I'm looking for a way to make a more systematic approach where we can use larger volumes at an industrial scale. So a more systematic process can be repeated over and over again, which would make it easier to process the materials. To process the blades, but also process and reuse the materials that come from, because I appreciate that the blade as an integral structure is quite difficult to reuse. Being very large, it leaves a big mark on the objections you're going to design. So it's more of towards one of the public applications, perhaps.

So I saw segmenting into panels and beams, and other construction elements as a potential solution. And then, if you come into the area of standardised pedals and beams, you look at areas where standardised panels and beams are used, and then you end up in things like the built environment, furniture and those kinds of areas. I did a furniture piece which was a very straightforward application. I mean, there are not a lot of very high demands on it.

It has to be structurally sound, and it has to be appreciated by the audience. But it's very easy to assess like that, and it's a more or less stand-alone product. But then again, you need to find volumes. And I did a little back-of-the-envelope calculation on my picnic table. And I estimated that about 150 of those tables would be produced out of a single blade, which is big fun, but it doesn't make that you can use large volumes of the material for that application. So I needed something with a larger scope, and that's how I ended up in the construction applications. That's from a philosophical point of view.

And then also, from a more practical point of view, it is a material with high strength and mechanical properties. It would be useful to reinstate them where those beneficial characteristics would also be used.

What are the possibilities and challenges of the material that you have experienced?

I think the opportunity of the material as such is that it's a pretty high-end material. It's very stiff yet relatively lightweight and strong as well.

If you dissect a wind turbine blade into different components, then you'll see that the panels that come out of it are made of a sandwich structure that's strong and stiff yet lightweight. And then you have the beams from the spar caps, which are really strong. So that's the strength heart of the unit, and then there are light panels outside of it. there's a very clear benefit in terms of mechanical performance. In addition, if you treat it well, it can last for a very long time. Because basically, it does not corrode or deteriorate out. It is a very stable material. So, I think, from a very pure material properties point of view, those are the main benefits.

And then, of course, on the other hand, there's the benefit of the supply. There are a lot of materials available. And there's a good story in it. This is a sustainable pathway for reusing these materials because we don't have a very suitable exciting path at this moment. But actually, that is not much of a benefit but more of a need. We need to do something useful with these materials because there's no suitable recycling pathway yet. And the other ways that we have now are just destructive in many ways.

Challenges, I've listed most of them in my papers so you can refer to those. If you are going to reuse a material like this in a secondary application, your secondary application relies on the initial specifications of the original product. Usually, if you're designing a product, you can set your specifications. There are many things you don't rely on as much you just specify, and then you find a solution to match those specifications. So there's more of a backwards and forwards in that, more of a discussion between the material availability and the application you want to achieve. So there is a conversation between those two, and that's at the point of geometry. So does your geometry line up, does your well, and then you come into all kinds of specifications you need to fulfil.

If you're looking at applications in the built environment, then you're looking into fire safety, structural integrity certification, how to process the material, how to cut the material, and how to do your calculations. They are all well-known specifications, sometimes it met, but sometimes it did not. There is a lot to find out about this, and there are a lot of gaps that need to be filled before we can implement this material at the large gap.

Possibilities to calculate the structure ability of this material?

Theoretically, I think you could do very good modelling. So you have a model of the blade, and you have the data of the wind conditions it was exposed to. Then by combining those, you could estimate the properties when you obtain the blade. That is modelling, and you need to have good trust in the model to trust that the materials have quality. Then there are some other approaches, some studies, such as the re-wind consortium, for example, has taken. They sampled out of the blade and took destructive testing on them. So that you know what is the property. And there are some more varieties on this…

So you can do it purely based on the models and obtain data, or you can do it very locally and test with marshall motor or do just very big of dimension just to make sure that you don't run into any troubles.

From your research, approximately 55% of a wind turbine blade can work as a structure. How about the other parts, such as the root and the tip? Does it mean they should be removed or not contain structural responsibilities?

That's exactly what I signalled that should be further investigated. They are still interesting materials, but the route has very thick laminate and a solid curved shape. It is a plane cylinder with an approximately 10cm thick solid glass fibre laminate. It is hard to process and find a direct reuse option. And the tip has much thinner laminate but is also more strongly curved or double curved, which makes it less likely to find a direct reuse solution. I'm confident there are probably good opportunities for both, but it would take some more effort to find suitable solutions.

What is your perspective about the lifetime of the structure made of WTB?

It will depend highly on the type of loading scenarios it will be exposed to and the environmental conditions. Indoor use will have the potential to last longer than outdoor use. As a little note, it can last forever, which is the problem with this material. Another note is that the resin is not very UV resistant. So if you expose bear epoxy or bear polyester to UV radiation, it will start to discolour and disintegrate.

Some of those blades have Bansal wood as a core material, and if the Bansal wood is exposed to water, it will absorb water, decompose, and deteriorate well. So it can last forever. But you have to take proper action to make sure that you protect the material well.

If you left that blade more or less intact, they would have to worry less about exposing the core materials. However, the coatings on the blade can also wear out and still expose the underlying composite material. For example, five blades were used in Rotterdam, the Wikado playground. There was a paper written by one of your colleagues from the architecture on how these blades performed after 20 years. They found that at some points, the coating would wear out, or at some points, the resin would start to reach out. It's just exposed to the environment.

What is your experiences with multiple-use cycles of the wind turbine blades?

Before designing new blades, we should consider what will happen at the end of their initial use cycle. Looking into the future, we have to consider what technological availability or processes will be available to handle the blade and what type of demands you would like to fulfil. So there's a lot of planning in there. So you could try to pinpoint a fairly specific use case and then design your blades to be usable or reusable.

But it also leaves a larger risk. Because you don't have a good plan, you are less certain about these specific use cases, which will be relevant 25 years from now. So it would be valuable to think we have to design for a range of use cases, and they are sort of uncertainty that you have to address in the design. And I'd be very interested in investigating further.

Does this lifetime also work for furniture, like the picnic table you have made?

It would depend on your application. The picnic table could last for 25 years. And then people get bored of looking at the same picnic table. But as it is indoors here, I do not see any reason why it should fail somewhere in the next 25 years. It just needs a little care, a little maintenance polishing up, and maybe redoing the paint every once in a while. But easily it will be decades.

Interview Tillmann Klein

Regarding the building's skin, Tillmann Klein was invited for the interview. He is a professor of building product innovation at TU Delft. He has been there since 2005 and completed his PhD in 2013. Besides working in architecture and building technologies for many years, at the same time, Klein is also leading the Façade Research Group. He is the editor of the Journal of Façade Design & Engineering and the project leader of the Leasing Facades research.

In general, what is your perspective on adapting wind turbine blades in the building's construction?

The problem is that it has a very distinctive shape. They are very strong, durable, and flexible. So using it in construction is something that you need to understand the property of the material. Constructually, you can say, okay, it is over the dimension of the system, and I will replace other materials which I normally use for that building. That is the benefit you create. Instead of using new components for the building, you use the wind turbine blade, which otherwise does not have other uses anymore. That is the effect that I understand. The only problem is the distinctive shape; you have to design with that.

Indeed the form of the material is distinctive. Normally in architectural design, we have 'form follows function', and now we have another way around. To clarify more about the structural quality, I will have a discussion with a structural designer and an engineer from the faculty of Civil Engineering at TU Delft. How about the ability to adapt this material on the facade, such as the sun shading, facade skin, or exterior cladding on the roof?

Facade cladding or sun shading is something to take into account because you have joints in between different blades, which have distinctive shapes. So you have to make sure that it works. You can have overlapping types of cladding. For the massive construction of this type of function, you can cut the blade into smaller pieces and use it that way. This way, it will be related to how many blades have the same dimension that you have found.

In a wind farm near Eemshaven, there will be 102 blades that are 35 meters. They will be decommissioned in and around 2030.

That is a big number, but it is good when you look at that. This material will gonna last a very long. In the manufacture, they were made for dynamic loads, like the wind load. In the structure, they will not be so many dynamic loads like that. Even if they are in the outdoor weather, I do not see why they would degrade. They will last very, very long. The only thing that can become a question is how they will be looked like in close. Normally you do not see them so often because they are very high up. It is necessary to see what their surfaces look like. Maybe you can coat them, to make them look the way you want.

The material itself can last very long. But in terms of regulations for buildings in the Netherlands, what is the lifetime of it each building's element?

There are no precise regulations like that. What we have is general restrictions on certain components that we believe they should last. This means we do not need to replace them if they are still in good condition. For turbine blades, I believe they are very strong and very sturdy elements.

They might be over dimensions anyhow. This might be related to how you calculate them for the structure part and how you test them. But I would not be worried about something happening to this structure. You may realize if something happening after using it for a long time.

How many years that the material will be durable as a facade?

The number of years that turbine blades will last as the building's facade is uncertain. It is very long since, over time, they wear just by UV light and weather. They are made for much more difficult situations than facades. It is also a matter of surface treatment. If you coat them regularly, they will go on forever. However, that would be more a matter of aesthetics rather than life extension. That stuff does not rot.

Could you share more about the maintenance process for this type of facade?

For the maintenance process, taking the 'bathtub' museum in Amsterdam as an example, its surface was made with a gel coat, which is a paint. You have this white or coloured paint, and you also have it on sailboats. That is basically a kind of painting that was sprayed into the mould. And then the elimination is on top of that when you take it out of the mould, right? The gel coat has this nice surface. It is a very sturdy coating, but what happens with time is that surface gets appears chalky due to the UV light. So you need to polish it and put wax on it. That is what you have for boats. So I can imagine that this is also something you have to do once in a while with this type of material.

But you also, you know, also aluminium, panelling, you also have to clean it. It can also lose its shine, but you can solve it by polishing it. Just like a car, once in a while, you need to give it a good polishing job. What happens is that the surface is relatively smooth than with time; some parts of the surface rot, and in these gaps, the dirt is getting into it. What you normally do with that is polish it down. You grind down the peak, and you fill the valleys with wax. You have to basically clean all kinds of facades, like aluminium facades, which you have to clean once in a while.

Another alternative, for example, is Trespa. It is a material that is a composite of layered paper and raisins pressed on high pressure. Sometimes they make furniture of it. For facades, you can get them in all kinds of colours. It's a plastic element that is very much used as a facade. It is super sturdy. I have it as a kitchen countertop. They were not cleaned at all. Once in a while, you need to clean it. Maintaining this material is not for safety reasons. It's just really more for the looks. For panels that are five or eight millimetres thick, right? They are not going to fall off. They don't look that nice anymore, and then you can have a surface treatment like a car. When you don't do anything, it gets greyish-red. If you polish them, the whole colour comes back.

So rainwater cannot clean the dirt on these facades if I understand correctly?

If you see it, you know, when it turns a bit dirty, you don't really see it, right? You also have bricks. Bricks sometimes stay there for 50 years, and no one is doing anything. But sometimes, you see where the brick facade is just cleaned. And you see, it's a much lighter brick than you thought, you know, old buildings are always dark brick buildings. If you're cleaning, they got reddish, right, but it's not. You don't clean them because they deteriorate; you clean them because sometimes you need to improve bricks, depending on how you use them. If you have a brick and you have a cavity behind it, it's not an issue, but sometimes you have massive brick walls. It's good to impregnate once in a while, but first, you need to clean it.

Those facades they don't really low maintenance, but once in a while, you have to do something about it.

How often do we need to clean the material? For instance, the surface of the sailboat or the aluminium facade? What are the impacts if we clean it or polish it regularly?

Cleaning the sailboat is one thing, but the polishing job takes more effort. But when you bring a new wax, cleaning the boat is easier. At least one time a year, you should give the boat a good polishing job which brings on new wax to protect it. For the facade, it will be longer.

For the facade, for example, if you take an aluminium facade, technically, you don't have to clean them. They are not going to fall down, but they're going to look a bit shabby after a while. If you don't do it after five or ten years, it will cost much more effort to do it than doing it in 1 or 2 years. Most clients don't want to spend money on it, but the professionals say, no, it's cheaper. If you do that more regularly, in the end, it is cheaper than waiting too long when you have to get really dirty stuff off.

But, you know, what the environmental impact of these cleaning is, I cannot tell you. That is surely an interesting question.

For wind turbines, I don't think they clean them. What I know is that they sometimes buy old windmills, which are not turning at such high speed. For the new big one, their wingtips go with a very high speed. I have been on a windmill once. It’s very, very cool to go inside and be on the top. They explained that for the new big and bigger windmills, there is more wear on the wing tips at the end because they go very fast. And when it’s rain and hail, it really wears the wing tips. So every once in a while, they had to recoat the wingtips just to make them last longer. And the old windmills didn't have that problem because their wingtips turned not so fast. So they're not so much affected by rain or hail.

When you have it in a building, I think you just rather clean that for the looks, for aesthetic reasons.

Besides, I think the furniture is what you need for the surface to be nice. I'm sure they coated them; they put a coating on top.

Do we also need to clean or maintain the joints of this material? Such as the steel frame or metal details that carry the cladding elements?

No, no. You have to design the joints. So they can last very long. You don't, you know, don't need to maintain the joints. Especially if you need all the detailed things, you have to use stainless steel. If you build close to the sea, which has salty air, you have to make it with a good construction that doesn't rust away.

They had some problems that happened for some buildings in the 60s. Those big old housing blocks. On a noise, they were built with steel anchors. And some of them collapsed. So today, you have to have the cladding with breaker big brick facades. They're using stainless steel anchors, so that doesn't happen.

I think this is really more of a structural problem. That's something you need a structural engineer to help you design the connections. We can do it, but normally, as the architect, you don't do that. You need to make sure that it will be designed properly, but you don't design it yourself.

And structurally, I'm curious what the structure engineer says, but I think normally a windmill is using blades like that, right? But now you're going to use it as a column or as the beam, so it's a very different way of using it. The tricky thing is that it is just all over dimensioning. If it was shorter, it could be more stable.

Interview Eric van den Ham

The potential of WTB in the services part will be elaborated by Eric van den Ham. He teaches climate design and building physics at the Faculty of Architecture & the Built Environment at TU Delft. According to the faculty, in energy performance assessment of buildings, he is a specialist who has over 30 years of experience as a climate design consultant.

In general, what are your opinions about the scheme of expanding the lifetime of end–of–life wind turbine blades?

For the blades, the material itself can last forever, but I think the reason you exchange its abilities for other reasons is that it's so you have this scheme. Okay, structure, the longest period, and all the other things have a shorter cycle. Because the materials are not functional anymore, but this is because of functional reasons or whatever. So, in the end, you can use this material for as long as you want. If you can make a building, there's a structure. That this is the most sustainable solution because that will last the longest time.

The problem is that these things are huge. The blade itself is a huge duct. And in some buildings, you have huge ducts. In a large theatre, for instance, you have ducts size of a meter. So they can be used directly as air ducts. Then you have to use the full product or how it fits.

You can also put it vertically because it's strong enough. One of the best ways to use it is to make use of literally the strength of the product. You cannot use this to replace the conventional structure, you have to come up with new ideas and new applications that you have this new product in the building industry, like your references.

What is your opinion about integrating this material into the building's services, for instance, the air and water system?

Air ducts, like I said. They're usually made of aluminium or steel. They come in different sizes, varying from more than the one-meter in diameter to 10 centimetres in diameter. Then you have air handling units. These are basically large boxes with a lot of components inside. They have to be sheltered. So when if they're on the roof, they have to be sheltered. That the shell of the air handling unit, it can be made out of 40. It is just to protect it from the environment.

Besides, it can be a water container. We have the whole water system in the building, such as the pilot and the wastewater. These are usually made out of PVC. You also have rainwater storage. That is more and more common nowadays. So you have to have plastic rainwater storage tanks. I can imagine you use a big wing as a rainwater storage tank. Usually, these are boring black plastic tanks. They can be huge. So a rough calculation of the volume inside the wing, based on the dimension of it that you found. So if I average it out, I would say, on average, 1 m2 serves over a length. If you would use this in rainwater storage, it will be ranging from 10 to 40 cubic meters. It's a small wing of 10 cubic meters, and it's a very large one with 30 or 40 cubic meters. And that's really useful for a storage tank.

Do they need to be maintained regularly? Normally how can they do that?

There's no need for maintenance. Every now and then, it's emptied, and they will spray it inside after approximately 10 years or more.

A nice thing about this is that you can also put it above ground or partly above ground. Normally when it is underground, it is the ugly black plastic tank. When you use the wing to make it and put it on the ground, besides the accessibility, as a wing, it can be made as a part of the landscape. It will be replaced or changed easily, compared with the underground tank.

How about other systems?

We have the whole heating system. But I do not see any applications for them. For example, the radiator is fairly standard. That does not really make sense to remake it with blades.

But for the air system, it is very potential to make a shelter for the air units. When you look at all those buildings, you see all the stuff that's on the roof. They are aluminium or metal boxes on top of the roof. These units have to be insulated and are even considered quite ugly. You can think of using each part of the wind turbine wing as a nice aesthetic cover. They will also play as sculptures on top of those roofs. Almost every building now has this kind of stuff: housing or office buildings, or industrial buildings. These shelters typically have a life cycle of 15 years.

So, we had applications of the wind turbine blade in the water and air system, not for the heating facilities. How about the electricity system?

It is possible if you can make some kind of ducts, but then we have to assemble it. For other parts, such as electricity boxes in the technical rooms, you can apply them there, but no one is going to see them, so it is not for aesthetic reasons. And these boxes for the electricity system are really standard. They require acoustic insulation. I think it is more sustainable to use the material that they often used. Another approach is what we usually do, placing these things on the roof with the PV panels. They can be made of the cheapest materials; then you put the shelter to protect it. Especially when we have it on the roof, you can replace them with way more parts of the wing. And then they can become part of the architecture.

Related to these services, but outside the building, the electrical box on the street is also a potential option to adapt parts of the wing. We have to design the connections, of course, and then you have to assemble them from different parts. Then you can make that urban furniture instead of a plastic box. These sit there for 20-30 years.

Are there any other applications that?

Another thing just came to my mind is sun shading. It belongs to the facade part, indeed. But you cannot restrict me to a limitation of services and installation. I think it's really possible to make very nice sun-shading devices.

Interview Felix Tarantik

Toni Egger and Felix Tarantik are founders of a design firm in Switzerland and southern Germany. Their furniture made of wind turbine blades has been presented at Milan Design week 2019. The collection includes desks, coffee tables, stools, and bookshelves. The dimensions of each piece varied depending on the type of WTB used. The desk is approximately 280x90x75 centimetres (length x width x height), and the shelf is 215x332x45 centimetres. Due to their function, extra materials were added beside the WTB, such as a glass plate for the desk and a leather cushion for the stool. Each piece of WTB in each product was coloured with a layer of high gloss paint.

I am glad to see you today, Felix!

Very nice to meet you, and excuse my beautiful sweatshirt. We have a Christmas party later in the office today. This is the best Christmas already.

Haha true. I just found your projects just recently, a lot of colourful and luxurious pieces of furniture, especially the one that was made of wind turbine blades. Could you share about your team and your journey to work with wind turbine blades?

Toni Egger and I, Felix Tarantik, founded Tarantik & Egger in 2015 to realise extraordinary design projects. We both hold an M.A. in Design from the University of Art and Design in Basel, Switzerland, and live and work in Switzerland and southern Germany. Being this close to the Alps, where ski gondolas are a typical sight, we were fascinated by their quality build. Our first project was turning such ski gondolas into saunas, “Saunagondel”. We presented it at the Salone del Mobile in Milan in 2016, getting press and selling them since then.

In 2019, students from the University of St. Gallen, Switzerland, approached us with a question: “Can you design products from old wind turbine rotor blades?” They’ve seen our Saunagondel at an exhibition, and because both projects have upcycling high-end industrial products at their core, we collaborated. The students had access to the material, and we designed a set of indoor furniture. Together we presented in Milan in 2019.

How did you come up with the idea of producing furniture with wind turbine blades on a large scale?

We wanted to impact the material as little as possible because it is incredibly hard to machine it, and the incredible sturdiness comes from the original form and build. At the same time, we wanted to move it into the home, the most extreme difference from the high-up outdoor place it originally is. We, humans, interact with tables, chairs, etc., multiple times each day and look at them and feel them constantly. This is why we developed our indoor furniture series using wind turbine rotor blades. To bring the unique form and high-end material close to our lives. With that, also the challenge of how to recycle this material comes close to us.

Besides couches, desks, and bookcases, since 2019, are there any other experiments with wind turbine blades that the company has worked with?

Recently what we have designed is a lamp. Besides that, there are multiple other opportunities, even outdoor furniture, because the material is sturdy, and there are endless possibilities with this material.

Normally furniture often has a limited lifetime; what is your opinion or vision, or expectation of the lifetime of furniture made of wind turbine blades?

I want to challenge the question. I wouldn't read it as the physical life of the product, but it's the societal lifetime of usage. Because you don't remove the interior of an office or a space plan after 20 - 30 years because it's broken. You remove it because you want to change it. So it's not because the furniture or the objects are broken when they need a replacement; it's because society or the people, or the group using that space has new needs or change needs.

In other parts, I think we always need to think about what lifetime. Do you need to replace something because it is actually broken, and you replace it with the same kind? Or do you actually want to replace something because maybe something's out of fashion? You don't wear your T-shirt anymore, and you buy a new t-shirt not because your old t-shirt is not good, but because it's your old t-shirt is out of fashion.

I think this applies to our furniture, so from a material point of view, the lifetime is pretty much endless. So for stools, their leather cushions can last for 20 - 50 years. For bookcases or desks with glass and wind turbine blades, it is too much longer.

So, it's not a question of how long it will last. It's a question of how soon we want to replace it. And then it's a question about culture, trends, fashion, and sustainability. So obviously, there are tons of things around that. Many good objects, when they were designed to a certain quality, last almost forever.

As these pieces of furniture have a unique design and can last very long, how are the possibilities for the users to change or upgrade them?

I think it's a good question. Furniture is updatable. In this case, with the rotor blade material, I think it is, in a very good way, actually. If you do not alter it too much like we did not, we kept its original structure and form or changed it as little as possible, there will be more possibilities. We transformed it into furniture for a really new use. But you could do that again at any point in time. It is the changes that we applied are a kind of sanding it even and colouring it. Painting it with very high-quality paint, but you could easily remove the paint, as you can repaint it or you can change it into any other form that is more altering than before.

So the potential for future changes in our design is incredibly high because the original changes that we applied were very low. I think it is like a bank account of possible changes. So when you end up in the first upcycling, when you withdraw much money from the changes bank account, you only have very little left for a future change. But if you withdraw only very little in the beginning, you have a lot of potential and money left for future changes. And this is what we did.

We did change the wind turbine blade very little in the beginning, so even after 50 years, the table can be updated into something very, very different.

Do these pieces of furniture require any special maintenance?

When it's indoors, nature doesn't have an effect and it needs to say maintenance as any other indoor furniture: to be wiped down once in a while. As long as you don't harm it, you don't need to maintain it. The other case obviously is true for outdoor furniture, when it's exposed to the weather. Then you need to clean it regularly every year at least.