Composite wind turbine blade recycling - value creation through Industry 4.0 to enable circularity in repurposing of composites

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Abstract. Composite waste, especially from wind turbine blades will increase foreseeably. The motivation of this paper is to develop new solutions to repurpose the global material stream coming from wind turbine blades at their end of use. Its suggested to use the composite structure for repurposing, differing from the available recycling methods that aim for a separation of the composite into fibre and matrix fractions. One key factor towards circularity in composite materials is converting significant amounts of composite material into multiple meaningful applications and products. Industry 4.0 can offer a systemic solution utilising robots and digital tools, such as a digital twin of a composite wind turbine blade. The digital handling of relevant material information can offer a new affordable material source to multiple industries, such as building industry or manufacturing businesses. Based on a digital platform the composite material can be made available for architects, designers and developers to repurpose composites into multiple new products.

1. Introduction

Wind turbines consist of various parts, like tower, nacelle, generator, blades etc. In the recycling of wind turbines, blades have been identified to be the most challenging part to recycle, due to their mixed material composition and the nature of thermoset reinforced composites [1]. Over the last two decades the installed wind turbine power grew substantially therefore the amounts of blades reaching end of use are foreseeably growing. Turbine blades have an expected lifetime of about 20-25 years, in case of repowering the wind turbine with new blades this lifetime can be shortened significantly. By 2025 the annual composite waste from wind is estimated to be 66,000 tons [2].

Currently there are various scenarios and technologies dealing with turbine blades after end of use. Landfill is one scenario often used while there are various composite recycling technologies at various technological readiness levels [TRL] available [3]. The available recycling technologies aim either to separate the composite material in a fibre and matrix fraction or recover the materials energy value within thermal recycling processes. With perspective on the waste treatment hierarchy the available wind turbine blade recycling solutions are addressing the two lowest options, recovery and disposal. None of the recycling technologies mentioned in [2] are aiming towards repurpose or recycling of the blade. Yet the composite materials used in blades
show excellent material properties and therefore would be ideal for repurpose scenarios.

Some showcases and projects make use of the structural qualities of recycled composite materials in a repurposing or a recycling scenario, for example repurposing the wind turbine blade into a bridge [4] a playground [5] or recycling into outdoor furniture [6]. These projects create value by utilising the structural qualities of reused composite material and integrate the fixed shape of the blade into the repurposed product. Single repurposing projects show the possibilities to climb up the waste treatment hierarchy, yet it might be difficult to match the global amounts of recycled composite materials.

This publication is proposing a scenario for Industry 4.0 to improve composite recycling on a global scale by utilising the composites material properties and fixed shape. A digital twin of the wind turbine blade is gathering relevant data including shape, material quality and mechanical properties. This data can be used to predict the blade lifetime and for maintenance and service. At the end of use, the digital twin data is the basis for material qualification and certification needed for repurpose solutions. Designers and architects use the geometrical data of the blade for their repurpose designs. Within architectural design, digital manufacturing tools allow, using the given shape of the blade and its digital conversion, to design it into new buildings and shapes. Once digitally designed robots disassemble the blade accordingly and reassemble it into its second life. This systemic approach can be used for building industry and others and is allowing for unlimited sustainable solutions in repurposing composites towards a more circular use.

2. Recycling today
Wind turbines consist of various parts, like tower, nacelle, generator, blades etc. In the recycling of wind turbines, blades have been identified to be the most challenging part to recycle, due to their mixed material composition and the nature of thermoset reinforced composites [1]. Over the last two decades the installed wind turbine power grew substantially therefore the number of blades reaching end of use are foreseeably growing. Turbine blades have an expected lifetime of about 20-25 years [7]. In case of repowering the wind turbine with new blades this lifetime can be shortened significantly. By 2025 the annual composite waste from wind is estimated to be 66,000 tons [2]. European Composites Industry Association, European Chemical Industry council and Wind Europe point out in their report “we are committed to promoting a circular economy which reduces environmental impacts throughout product lifecycles.” About the current turbine blade recycling situation, the report is stating “while various technologies exist that can be used to recycle blades, these solutions are yet to be widely available and cost-competitive” [8] so, the current recycling solutions are not yet fully applicable for global use.

2.1. Composites in wind turbine blades
Wind turbine blades are considered a composite structure, consisting of various materials with different properties. Although material compositions vary between blade types and blade manufacturers [4]. Typical materials in wind turbine blades are shown in Figure 2:

- reinforced fibres: glass, carbon, aramid or basalt;
- a polymer matrix: thermosets such as epoxies, polyesters, vinyl esters, polyurethane, or thermoplastics;
- a sandwich core: balsa wood or foams such as polyvinyl PVC, PET;
- coatings: PE, PUR;
- metals: copper wiring, steel bolts.

The combination of fibers and polymers, also known as glass fiber reinforced polymer (GFRP) composites, represents the majority of the blade’s material composition (60–70% reinforcing
fibers and 30–40% resin by weight) [4]. The shape of the wind blade from the root to the tip transitions rapidly from round to an airfoil shape. These airfoil shapes vary along the length of the blade. A blade can be divided into 4 main parts: shell, caps, shear webs, and root. Shells are designed to transfer lift, created by the shells, to the spar caps, then spar caps transfer the loading to the root. Shear webs keep the caps away from each other, allowing the blade to behave as a beam and retain its global stiffness. This structure is shown decomposed on Figure 3.

The most widely used technology to produce the wind blades is prepreg and resin infusion technology. Prepreg allows the industrial impregnation of fibers, and then forming the impregnated fibers to complex shapes. Currently, vacuum assisted resin transfer molding (VARTM) is the most common manufacturing method for manufacturing of wind turbine rotor blades. 3D woven composites represent a promising alternative to producing fiber reinforced laminates, and this technology allows producing spar caps with higher stiffness and lower weight.
Using automatization technology in the manufacturing process, allow increasing the complexity of the geometry of the blade, enabling to exploit the internal aerodynamic properties, and significantly increase energy [12]. The generic wind blade manufacturing includes 6 steps:

(i) Preparation of the mould;
(ii) Build-up of the dry-layers;
(iii) Resin infusion;
(iv) Adding the webs;
(v) Joining the shells and curing;
(vi) Demoulding, trimming and polishing.

2.2. Available recycling technologies
The main routes for handling end-of-life composite materials are landfill, incineration or recycling to which recycling has a number of approaches: mechanical, thermal and chemical recycling [4]. Currently, mechanical, thermal and chemical approaches have been used to recycle composites. The composite recycling is still an immature area. This means the developing techniques mentioned above still need to be optimized to produce higher quality recyclates and improve resource efficiency [13]. These technologies have different properties, advantages, disadvantages, and technology readiness level displayed in [3].

2.3. Limitations in state-of-the-art methods
Despite the number of recycling technologies presented so far, they all have major drawbacks and limitations, thus making them close to irrelevant on industrial scales. Energy recovery from the incineration of wind turbine blades is made difficult by their high glass fiber content which prevents an effective burning of the parts [14]. Once incinerated, the remaining ashes may be landfilled, when it must be avoided at all costs being the worst end of life option. Mechanically grinding the blades and reusing the shredded parts as fillers for other products is an interesting option. However, all the companies that had implemented industrial scale grinding have ceased operating [14]. The wind industry is pushing the use of the shredded material as filler for cement [8] but it lacks industrial partners to complete the process. It must also be noted that the use of the composite waste for this matter makes no use of its structural properties and therefore significantly lowers the value of the material [14]. A Danish company, Miljøskærm [15], processes shredded GFRP into thermal and acoustic isolation panels. It is however not operating on an
industrial scale yet [14].

Thermal recycling processes, such as pyrolysis or fluidized bed, allow only for the recovery of the fiber material, and it comes at the cost of significantly diminished mechanical properties [14]. The Danish company ReFiber made use of pyrolysis to salvage the glass fibers but was terminated in 2007 [1]. In the same way, chemical recycling processes, despite the recovery of both fiber and matrix components with an acceptable quality, are not operated at industrial scale. This is because the processed materials are more expensive than in their virgin condition. Therefore, the state-of-the-art methods for recycling wind turbine blades are either responsible for low value applications of an originally high value material or are more costly than buying virgin material for the producers, while providing limited performances. Hence, solid waste disposal is less costly for wind turbine blades than recycling [16]. In the Netherlands for example, there are no recycling options under the government-fixed threshold of 200 EUR/t, meaning that landfilling is still accepted for wind turbine blades when composite waste landfilling is banned [8].

2.4. Reuse of structural composite parts - best practice
The currently available recycling technologies for wind turbine blades, introduced in the previous sections, have their limitations as they are all within the three least favored levels of the waste treatment hierarchy (Figure 1). They offer only low value applications for the recycled composite parts. It is of a greater interest, on all the plans, to make use of the structural nature of composite wind turbine blades, and therefore achieve higher value recycling. This is characterized by methods belonging to the 2nd and 3rd most favorable levels of the waste treatment hierarchy (Figure 1), Reuse and Repurpose respectively.

2.4.1. Reuse methods
Reuse recycling scenarios consist in the refurbishment of decommissioned wind turbine blades which are, mostly, still usable after their service life of around 20 years [14]. It is by far the most desirable recycling option, since it extends the blade’s life beyond its intended service life while retaining its original purpose and making full use of its design. However, it must not be forgotten that this solution depends on the blade’s condition and that, at some point, it will not be possible to reuse a blade anymore. Then, repurpose methods should be envisaged.

2.4.2. Repurpose methods
If it is not possible to reuse the blades, they can be repurposed. Several applications can be found where it is made use of the structural nature of the composite wind turbine blades. The architecture office Superuse Studios has conducted several projects of repurposing blades for urban furniture through the Blade Made initiative [18]. They made use of decommissioned blades to design a playground, bus shelters, public seating and a signpost for a recycling centre. This extensive use of the structural nature of the blades goes to show that they can be repurposed and at the same time replace virgin raw materials that would be used otherwise to build these structures. A similar use of blade parts for urban furniture was made in Aalborg, Denmark, as a bike shed [19].

There have been several other design ideas involving decommissioned blades for civil engineering applications that benefit from the structural properties of the blades. First, affordable housing for the coastal regions of the Yucatan province in Mexico was designed (Figure 4), using blade material for the roof, door and window frames and elevated foundations [17]. Another use envisaged is that of poles in power transmission lines [20]. Finally, blades inspired some bridge designs. Stijn Speksnijder designed a slow traffic Bridge of Blades as his master thesis at the Delft University of Technology [21]. Similarly, a pedestrian bridge has been designed, using blades as girders [22]. Superuse Studios also designed a bridge using two blades for the city of Aalborg, Denmark, and is waiting for its installation [18].
2.5. Motivation for new approaches
In the perception of the authors none of the currently available recycling technologies are yet able
to handle the global composite material waste stream. Cost competitiveness and availability are
two of the reasons for this [2]. We further estimate scalability and value of the recycled products
from composites as significant factors. Looking at handling large amounts of material within the
available composite recycling technologies, this is mostly achieved by a “uniformation” of the
composite material. One example is cutting and shredding a composite blade into small parts in
order to run pyrolysis efficiently. This uniformation comes with a significant loss of mechanical
material properties.

On the other hand, there are several projects repurposing the shape and the mechanical
properties of the wind turbine blade to create bridges, playgrounds or furniture. The challenge
hereby is scalability, in order to repurpose 14,000 blades predicted for Europe in 2023 [23]. The
motivation for this paper is to develop a recycling method utilizing the outstanding mechanical
properties of composite materials and being scalable at the same time. The method should be
able to create value by utilizing the growing global composite material waste stream and turn it
into a circular material economy. The mindset of this principle sees composites as a source for a
high-quality material. The idea is applying Industry 4.0 technology to bridge the gap between
material specific repurposing and scalability.

3. Industry 4.0
For manufacturers in high wage countries, a major strategy to keep production costs competitive
without outsourcing production is to increase the level of automation, i.e. by introducing
robots as highly reconfigurable manipulators for product assembly. Such reconfigurable and
agile robotic solutions are of particular interest in high mix/low volume production scenarios,
where manufacturers offer many product variants between which production is often switched
[24]. The resulting complexity of controlling agile robotic solutions to be fit for manipulating
high amounts of product variants is clearly demanding. The paradigm of Industry 4.0 aims
to resolve such automation complexities by means of digitalization and the implementation of model-, simulation- and data-based planning and control methods [25].

The essence of the paradigm of Industry 4.0 is to complement the physical scenario with digital representations of the relevant assets (i.e. product and production system) and then to solve planning and control in the digital realm first, before executing the solution in the physical setup. Such an approach, based on the use of Cyber-Physical Systems (CPS) has opened fundamental opportunities in architectural robotics, by shortening the distance between the phases of design and making, and ultimately, has provided a fundamental platform for customization and bespoke manufacturing.

3.1. Digital Twin

Digital Twins were first mentioned in the context of Product Lifecycle Management [26], and later became an integral concept of Industry 4.0 [27]. In 2018, Gartner deemed Digital Twins as one of the five major technological trends of the next decade [28]. However, the term lacks a unique definition, and its interpretations range from “digital interface of physical assets” to “simulation of physical assets” [27]. Based on [29] and [30], we understand Digital Twins to be comprehensive virtual replica of physical robotic equipment regarding the exposed functionality (e.g. to command robot motions identical to the physical robot) as well as the relevant parameters and behaviors (e.g. to set joint velocities or to stop at collisions). Such replica allow for applying various 3D methods of simulation, planning and visualization as well as connecting to the physical robots and sensors for accessing their data from actual operations and controlling them based on the (simulated or real) data processed in the Digital Twin [29].

3.2. Industry 4.0 to enable circularity in repurposing of composites

Next to the obvious challenges due to extraordinary dimensions, production of large structures such as wind turbines and blades can be categorized as “high mix/low volume” production as they tend to be complex few-of-a-kind or even one-of-a-kind designs that are produced and operated in highly dynamic environments, particularly if it comes to offshore installations. Accordingly, also the recycling of wind turbines and blades is complex and can highly benefit from the application of Digital Twins to analyze and then control their recycling processes:

- Wind turbine blades like other large structures (e.g. ships and buildings) consist of an extensive variety of components vastly differing in dimensions, materials and production processes to make them part of the overall product.

- Wind turbine blades may require recycling operations in highly dynamic, often unique environments such as offshore windparks, where operations need to be carefully coordinated in time and space.

- Due to the complexity of the product and the production environment, automation of recycling of wind turbine blades requires flexible, reconfigurable, “smart” production systems based on digitalization and robotization.

Industry 4.0 is combining the Digital Twin approach with the physical repurposing environment, such as decommissioning robots, transport and automation solutions. Figure 5 is outlining a systematic approach of recycling composite wind turbine blades with Industry 4.0. The green arrows, ”Reuse”, ”Refurbish”, etc., denote the escalating options of treating the blades in subprocesses, often with various alternatives (red boxes). If reusing and refurbishing is not possible any more, the composite materials of the blades can be cut, the cuts can be shredded, the shreds can be milled and/or treated chemically (e.g. by means of solvolysis). For each of
the subprocesses and alternatives the incoming and outgoing materials need to be characterized and the the logistic alas well as the automation options of each of the subprocesses need to be identified, evaluated and selected (green, yellow and black boxes). The resulting material outputs of cutting, shredding, milling and chemical treatment can be used in various recycling applications (grey boxes).

3.3. Value creation in recycling of composite wind turbine blades

The previous chapters where introducing into the general possibilities of Industry 4.0 applied for large scale composite structure recycling. In order to create value for society and businesses it is benefitable to get up the waste treatment hierarchy shown in Figure 1. A 5-step schematic is outlining the structure of such a recycling method.

(i) Evaluation: geometrical and structural;
(ii) Digitalization: creation of a digital twin;
(iii) Computational design: architectural structures, product design;
(iv) Robotic composite blade disassembly;
(v) Transformation and reassembly: repurposed composite product.

An evaluation of the repurposing wind turbine blade will deliver data on geometry and surface quality, wear and tear as well as structural material parameters. The data can be gathered by scanning, non-destructive testing and production data from the manufacturer. The result of the evaluation is a classification of the repurposing blade. Based on this classification a later repurposing scenario can be determined.

These digital data will help mirroring each specific blade digitally into a digital twin. The digital twin allows to additional data sets as for example economical parameters, logistic data and relevant material certification. A digital twin can already be created while the blade is still operational.

Computational design can utilize the digital twin with the shape constraint composite structures to redesign and repurpose the blade into new products and architecture. At this point the original design will get digitally transformed into its second live usage. This process is possible while the composite blade is still operational.

Based on data from computational design, robots will disassemble the blade in the specific
segments needed for its circular use. Disassembly could be executed by robotic sawing and milling into pieces of the right size and specific material properties. For logistic reasons disassembly could take place at the wind turbine site.

Once disassembled the different pieces can be easier transported and delivered to its destination. Reassembly into the repurposed product or architectural structure could be executed by robots or manually.

4. Computational Design Approach for Circularity
The recent proliferation of digital tools has offered to the designers the possibility of approaching design with new perspectives. In particular, the use of computation has fundamentally shifted the essence of the design process, by the introduction of a data-driven approach. Through the use of computational means, the designer can easily evaluate a large number of design options in relation to various datasets, he can assess the performance features of a certain design [31] and establish strategies for optimization and differentiation. Moreover, access to computational design has allowed designers to customize workflows, create their own tools and engage with novel processes of construction through the use of digital fabrication tools and robotics. In the context of this work, computational design offers interesting perspectives in the informed manipulation of complex geometry, material and mechanical data, integration of design/simulation into a unique process based on data-rich digital models.

4.1. A computational design process for blade repurposing
One fundamental aspect of a digital twin in this work is providing high-resolution geometrical and material data into the digital space. Data from digital photogrammetry and LiDAR scanning can be nowadays easily converted into geometrical three-dimensional models. High-precision scanning techniques can provide data-intensive geometry, such as point clouds or large mesh, which can be conveniently translated NURBS description.

This fundamental step enables a form of abstraction of the blade geometry, which can be subsequently processed through its fundamental mathematical description. Available tools can be used to inspect existing models and retrieve underlying geometrical information, such as curvature principals and Gaussian curvature of the different areas of a blade’s shell. Once a specific design application is proposed with the re-purposing of shell elements starting from existing blades, it is possible to establish a design optimization where an existing geometry can be discretized into parts that match a target design within predefined tolerances.

A second approach can proceed with an initial analysis of the curvature and the extension of the various parts of a blade and suggest useful cutting patterns to obtain composite elements falling into classes of a gaussian curvature. In this case, the various parts can be used as a mechanically reliable substrate for further and more general construction purposes. This can be utilized as a lightweight structural core for certain architectural applications, relying on complementary techniques and materials to further complete the construction.

4.2. From Computational Design to Robotic Fabrication
In the repurposing of existing large-scale elements, the possibility of an integration platform from survey to design to fabrication is fundamental to reduce inconsistencies. Once cutting patterns over a blade shell element are defined, the physical machining of such elements requires the utilization of a large-scale facility that can operate with multi-axial cutting tools. Recent developments of large-scale robotic setups, where industrial robots are integrated with building-scale gantry systems, are offering solutions in this sense. Directly from design information, robots equipped for intensive CNC milling can be operated to cut effectively the shell elements into elements of different sizes and then sorted and stored automatically. Possibly, the same infrastructure can be used for survey and inspection, so that enough precision is ensured in
the geometrical analysis. Computer vision can be also integrated for an evaluation of potential material inconsistencies, tracing of existing decay, analysis of potential cracking patterns. This data can be then confronted with mechanical analysis of specimens that are physically extracted on the blade’s external body.

5. Conclusion

This paper has described the existing composite recycling technologies and the limitations of the different methods. It has been found that composite recycling methods described in [2] were working based on a principle of “unification” of the recycled composite material. This unification process is coming with a significant loss of mechanical material properties of the composite structure. On the other hand, unification is a principle to deal with the multi material composition coming from composite wind turbine blades. Further unification is offering a possibility of scaling, therefore the handling of larger amounts of composite is possible by scaling up the processes.

In contrast to unification of the recycled composite materials there has been different projects using the mechanical material properties in order to repurpose the composite wind turbine blade into different structures, such as bridges, kids’ playgrounds and others. These projects are however singular individual projects with a specific one-time outcome. Therefor a scalability of the solutions seems difficult to realize. These kind of projects may not be the optimal solution to address the global composite waste stream.

This paper is developing a composite recycling scenario that allows using the composite material properties and scalability at the same time by using industry 4.0 and digital fabrication. Industry 4.0 and a digital twin of the composite wind turbine blade is mirroring the fixed shape and the specific material properties of each single wind turbine blade. The specific data of the digital twin can be designed into endless designs for repurposed composite products. Digital manufacturing allowing for the specific decommissioning of each single blade and rebuilding into the repurposed design that has been digitally designed.

The developed Industry 4.0 based repurposing scenario is of theoretical nature and indicates significant benefits in improving composite recycling. It is suggested to investigate the specific value creation in composite recycling. It is further suggested to create a proof of concept in order to verify the theory developed in this paper.

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