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A digital process for reconstructing wind turbine blade geometry from point cloud data

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ABSTRACT: The first generation of wind turbines are being retired, and a tremendous number of wind turbine blades are coming out of service. Architects and engineers are developing re-use ideas for these blades and are wrestling with their complex geometries and materiality. This paper details a four-phase process for reconstructing the geometry of wind turbine blades, starting from a point-cloud scan and finishing with a digital model that represents the blade and its associated properties. The process builds on earlier work that created an airfoil database to store the normalized coordinates of publicly available airfoil profiles. This profile database is traversed to match airfoil shapes to cross-sections found in the point-cloud. Root, transition, and airfoil shapes are matched to cross-sections along the full blade to reconstruct the outer geometry. Based on data from the interior of the blade, the structural spar box is reconstructed. The addition of thickness and material property data allows for calculation of section properties at multiple stations along the blade. The resulting 3D geometry and the associated data is used for architectural design and engineering calculations to develop second-life applications for wind blades. The paper demonstrates the workflow through examples from a GE 37-meter blade and an LM 13.4-meter blade.

1 INTRODUCTION

Countries and political unions are setting ambitious goals in the coming decades to reduce greenhouse gas emissions from the energy sector, as well as adopt clean energy practices to mitigate the impacts of global climate change. These goals incorporate wind energy as one of the key methods of reaching low-emission energy production and cutting greenhouse gas emissions (Jensen 2018).

In combination with the growing number of operating wind farms, the output and efficiency of the wind turbines themselves are also growing. Since the 1980s, the diameter of turbine rotors has increased substantially – while early turbines had a diameter of around 18 m, turbines in development will have diameters nearing 250 m (Lefeuvre 2019). The growth of these wind blades has stimulated technological advancements in material properties and construction, such as the use of initially glass-fiber and now carbon-fiber composites. These composite materials offer lightweight manipulation, corrosion resistance, greater strength, and manufacturing benefits that aid in their rapid deployment. Despite these advancements, the lifespan of these blades is estimated to be only around 20-25 years on the wind turbine (Dannermand 2007).

Decommissioning blades after their lifespan presents a challenge for many wind farms around the world. Half of the wind turbines in operation in countries such as Germany, Spain, and Denmark are over 15 years old in comparison to the rest of Europe, where 28% of blades are nearing end-of-life (Mishnaevsky 2021). Europe is ahead of Asia and North America in terms of impending blade waste and will be the first group of countries and regulatory bodies that must address this waste challenge.

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When composite blades come offline, there are a few options for how to manage the waste material. In the United States, the most common solution is to send the blades to landfill. There are greater amounts of open land in the US and less regulation regarding the disposal of composite materials, as the method and location of disposal is driven primarily by market forces (Ortegon 2013). In Europe, where countries have stricter legislation on discarding composite materials, incineration is the predominant method of disposal (Mishnaevsky 2021). Incineration captures energy from the burning blade and is left with ash that will either be dumped into a landfill, used as filler material in construction, or as replacements for Portland cement (Larsen 2009; Nagle 2020).

To lessen the environmental impact of repowering or decommissioning decisions, there are growing efforts in reusing and recycling the blades at their end of life. As of now, there are no industrial scale solutions for blade re-use or recycling (Liu 2017). Current efforts focus on either using the blade in its original form or recycling the blade through chemical or mechanical processes. Decommissioned blades can be resold on the used turbine market and are often sent to smaller wind farms. In the Netherlands, approximately 20% of decommissioned blades are sold for this purpose (Mishnaevsky 2021).

Several researchers and designers have developed or proposed creative, adaptive re-use of wind turbine blades. Superuse Studios has created a playground, the City of Aalborg has implemented a bike shelter, Anmet has produced multiple sets of indoor and outdoor furniture, and Joustra and colleagues have worked with EcoBulk to establish a cascading system of products that have been prototyped from blades (“Blade Made” 2021; Eilers 2020; Joustra 2021; “Our Works” 2021). Our Re-Wind team (www.re-wind.info) has developed re-use design ideas focusing on structural re-use applications that take advantage of the strength and stiffness of the wind blade composites. In 2018, Bank et al. demonstrated the ability to slice wind blade sections to use as roofing on traditional CMU construction in Yucatan housing in Mexico (Bank 2018). Suhail et al. presented the structural analysis of a short-span pedestrian bridge using Vestas V27 blades as the primary structure (Suhail 2019). In electrical infrastructure, the Re-Wind team has proposed that the decommissioned blades be used as electrical transmission poles (Alshannaq 2021).

The potential for widespread re-use of wind blades in architecture and civil infrastructure will depend on the ability of architects to manipulate the complex geometry of wind blades and engineers to analyze structural re-use scenarios. The goal of the digital processes described in this paper is to provide designers with digital models of the geometry and properties of the decommissioned wind blades to facilitate re-design activities.

2 ASPIRATIONS FOR A “BLADE MACHINE”

This paper describes the development of a computational technology that serves Re-Wind in a larger process of reusing decommissioned wind turbine blades in creative and functional applications in buildings and civil infrastructure. The software, implemented within the Rhinoceros CAD platform, creates a digital twin that allows designers to explore how the blades can be sectioned, aggregated, or implemented as entire objects in architectural and structural applications. As greater numbers of wind blades are removed at the end of their lifecycle or are replaced by more powerful blades, this technology can enable a business of blade repurposing to operate at a large scale necessary to have a meaningful impact on the substantial number of blades anticipated to be coming out of service.

Advancements in this technology can aid in the analysis and digital recreation of other decommissioned building elements to be reused in architecture and civil infrastructure. The technology will follow a similar process as described here, moving from a scan of a physical object in its end-of-life state to a geometric model in which material and other information can be attached to facilitate structural analysis, fabrication modeling, CNC toolpath generation, etc.

The process of creating a digital version of the physical wind blade is called “Blade Machine” and builds off the work of Tasistro-Hart et al. and the proposed reconstruction routines using evolutionary solvers (Tasistro-Hart 2019). The process starts with acquired point clouds from LiDAR and/or photogrammetry and builds a number of blade models of increasing complexity by fusing data on the external geometry of blades with material thickness and engineering data such as material density, stiffness, and strength. The software currently operates in four phases, with each phase producing a functionally specific architectural or engineering model of the blade (Figure 1).

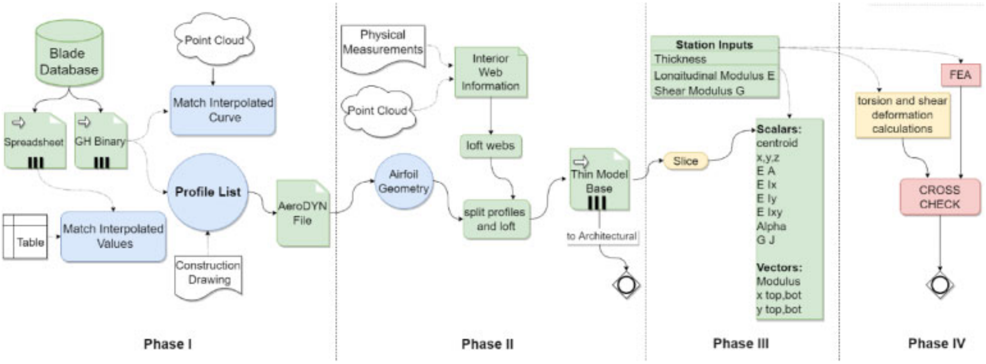


Figure 1. Logic flow diagram of the Blade Machine Phases.

2.1 *Phase I: From point cloud to airfoils*

Digital twin construction begins with the digital capture of the external geometry of the original turbine blades, through 3D scanning or photogrammetry. Decommissioned blades are stored in “lay-down yards,” to be scanned either in place or other areas clear of objects to reduce noise and occlusions. This type of scanning yields an accurate reconstruction of the blade’s outer surface as a point cloud. When possible, these scans can be combined with the scan of the interior of a blade. Once this operation is complete, the point cloud is cleaned and pared down in Cloud Compare to store the digital information in a manageable file size. The cleaning process entails further culling of noise and other artifacts such as other blades in the laydown yard. The cleaned point cloud is then imported into Rhinoceros, where the core code of the Blade Machine is hosted. Grasshopper, a Visual Programming Language (VPL) plug-in for Rhinoceros, encodes the Blade Machine functions. Many of the repetitive engineering calculations and matrix manipulations are completed using Python within Grasshopper.

Blade Machine begins by orienting the cleaned point cloud scan input from CloudCompare and taking cross sections parallel to the root plane along a range of desired Z-coordinates. The density of cross sections taken along the blade is higher in the transition zone between the cylindrical root and maximum chord length, as well as near the tip of the blade. The point cloud sections are comparable to airfoil geometries, which correspond to section cuts along aerodynamic structures (i.e.: wings, propellers, turbine blades). Due to the proprietary nature of manufactured wind turbine blades, the exact series of airfoils that constitute a blade must often be approximated. Phase I of the BladeMachine compares sections of the point cloud scan to airfoil shape that the Re-Wind project has aggregated from publicly available sources into an airfoil database. Some public airfoils, such as the NACA profiles, have been in use for a long time; whereas many of the shapes Re-Wind works with are developed with more recent computational methods. While a point cloud section at a given station can be matched with these public airfoils, it can also be fitted with an interpolated curve if the section is taken in a transition zone between airfoils. The profiles are stored as a list of (x,y) coordinates that range between 50 and 200 points to describe each airfoil (Tasistro-Hart 2019).

At a given station, the shape of a blade’s section is matched with to a selected airfoil profile from the database. The profile is superimposed over the selected cross-section of the turbine blade

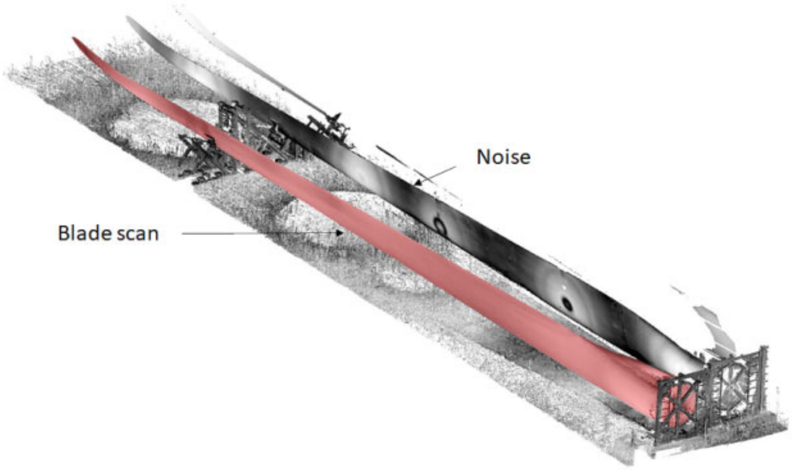
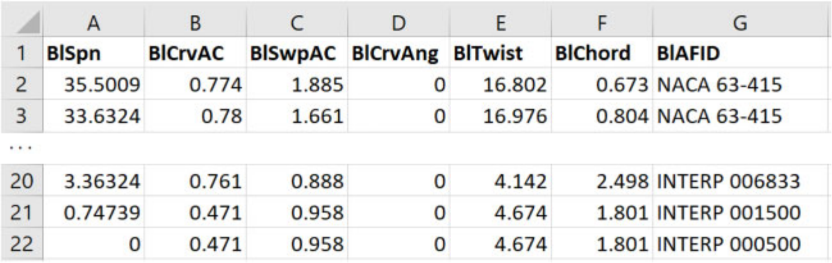


Figure 2. LiDAR scanned image of a GE 37 m blade taken in situ from the Smoky Hills wind farm in Lincoln County, Kansas. The target wind blade is highlighted in red, before cleaning surrounding noise of the grass, supports, and adjacent blade.

and manipulated to match the data more closely. These manipulations consist of rotations, uniform scaling, and translations in the X and Y directions. Using a combination of visual approximations and semi-automated manipulations, the operator selects the airfoil and attributes that best match the selected cross-section geometry. Once the desired properties are selected, they are written to an AeroDYN file describing the outer shell geometry of the blade (Figure 3). This process can be repeated for any station along the 3D scan of the blade.



	A	B	C	D	E	F	G
1	**BlSpn**	**BlCrvAC**	**BlSwpAC**	**BlCrvAng**	**BlTwist**	**BlChord**	**BlAFID**
2	35.5009	0.774	1.885	0	16.802	0.673	NACA 63-415
3	33.6324	0.78	1.661	0	16.976	0.804	NACA 63-415
...							
20	3.36324	0.761	0.888	0	4.142	2.498	INTERP 006833
21	0.74739	0.471	0.958	0	4.674	1.801	INTERP 001500
22	0	0.471	0.958	0	4.674	1.801	INTERP 000500

Figure 3. Example AeroDYN file output generated from Phase I, each row representing a station along the blade.

2.2 *Phase II: From airfoils to thin model*

After the analysis of the 3D scan of the exterior is completed and the full AeroDYN file is generated, the file is then used as the input for Phase II of the Blade Machine. While the focus of Phase I lies in finding the matches of known or interpolated airfoils, Phase II's focus is on incorporating the interior behavior and creating an outer shell from Phase I-generated airfoils. Phase II gathers the airfoil label and transformation factors from the AeroDYN file and plots the matching airfoil from the database around the found geometric centroid (BlSpn, BlCrvAC, BlSwpAC), using scale (BlChord) and rotation (BlTwist) information annotated in Phase I.

The interior of a wind turbine blade consists of a structural I- or box beam integrated into the shell and containing one or more shear webs. The internal web structure, such as the number and location of web(s) as well as the twist, differs between types of blades. Phase II generates a thin model combining the exterior information from Phase I with the described interior geometry. As the interior spar composite material generally differs from the exterior of the blade, the physical modeling of interior information is especially important for structural calculations in later phases. To transcribe the behavior of the interior of the blade, the input data consists of one of the following: (1) a series of measurements of cross-sectional slices of the same wind turbine blade, (2) an interior point cloud scan of the blade that can be oriented with relation to the exterior scan, or (3) manual modeling of the web geometry in Rhinoceros. The goal of the interior model of Phase II is to define the interior web(s) start and end locations, how they change or twist along the length of the blade, and how many webs exist. Based on the inputs, Phase II generates a surface to represent the centerline of each web. These surfaces are used to divide the airfoil into its respective components: high pressure leading edge, high pressure trailing edge, low pressure trailing edge, low pressure leading edge, any spar caps between the webs, and the web(s). This airfoil division and expression of the web(s) occurs at the level of the airfoil and is still represented as curves (Figure 4).

To create the outer shell and interior webs, each segment is lofted to the next respective segment: for example, high pressure leading edge (HPLE) at Station 0 is lofted to HPLE at Station 1, etc. Thus, the airfoils create thin shells that visually represent the interior and exterior geometries of the original blade. These shells and airfoil segments are baked from Grasshopper into Rhinoceros to create physical attributes that will be used in Phase III (Figure 4).

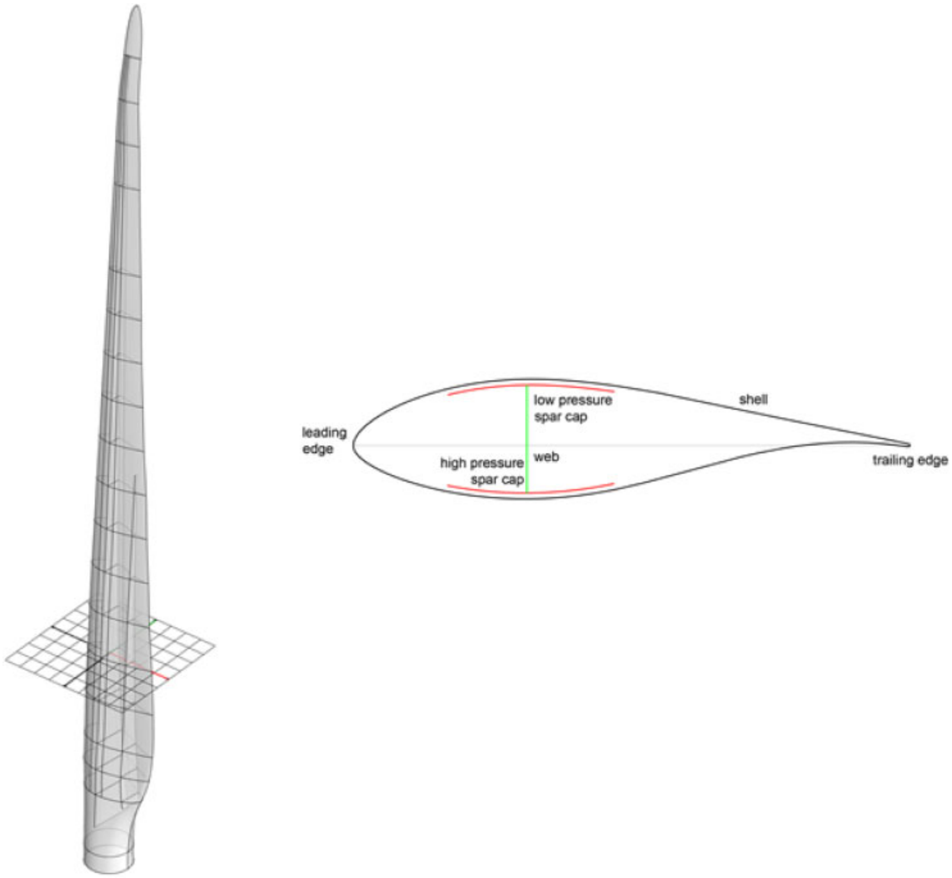


Figure 4. Thin model output from Phase II showing interior web and spar cap information.

2.3 *Phase III: From thin to thick model*

Using thickness measurements taken from cross sections of the original wind turbine blade, each airfoil segment curve is offset to yield the actual thickness. The thickness values are recorded for multiple areas along each airfoil segment, each web, each spar cap, and along areas of transition between airfoil segments. This measuring process has only been conducted in-person with airfoil cross-sections, but it could be conducted with the combined interior and exterior scan of a blade. Each set of measurements is gathered at each cross-section that has been cut and the measurements are recorded in an excel file that could be read by a Grasshopper script.

This process is currently conducted manually in Rhinoceros by physically offsetting each airfoil segment individually, forming a surface between the offsets, and lofting the new surfaces between each vertical station. When all surfaces have been lofted, and respective surfaces have been joined, the thick model is complete and is meant to serve as a digital twin of the actual wind turbine blade. Thickness measurements taken from cross sections of the original wind turbine blade, are used to offset each airfoil segment curve to yield the actual thickness.

2.4 *Phase IV: Engineering properties*

Phase IV of the Blade Machine combines geometric data from the three prior phases with physical and mechanical properties of the FRP composite materials used in the wind blades. The densities and elastic moduli of the elements in the cross section are then used to calculate the composite centroid of the wind blade, and the key section properties (areas and moments of inertia) needed for structural design. In most cases the shells, webs and spar caps are composed of different laminates, so the properties are assumed to be different for each of these elements within the cross section. Example output from Blade Machine Phase IV is shown in Figure 5 below. The output depicted in

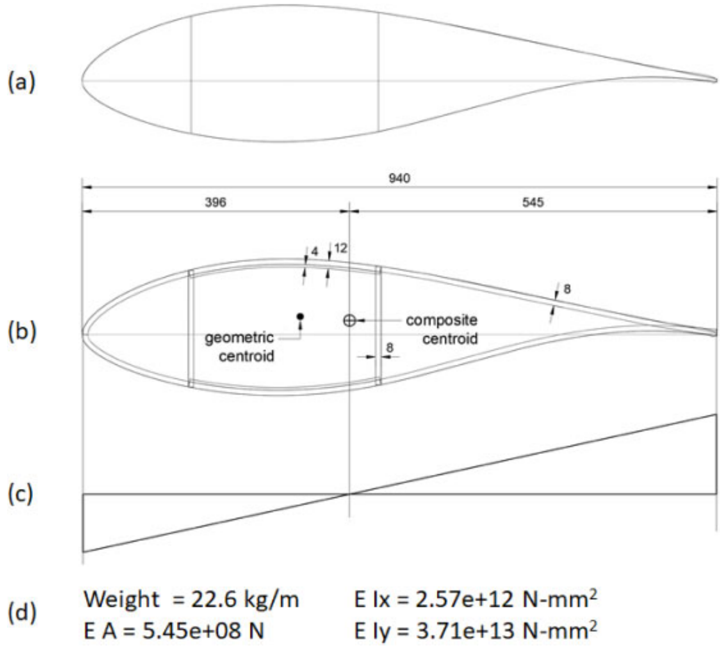


Figure 5. Phase IV of Blade Machine at one station along the LM 13.4 m blade (a) airfoil with webs from Phase II, (b) thick geometry from Phase III with geometric (weight) and composite (stiffness) centroids, (c) flexural strain diagram for edgewise bending, (d) composite section properties at this section.

Figure 5 is available for any station along the length of the blade after Phase II surface interpolation is complete.

3 FUTURE WORK

The vision for the Blade Machine is for the individual phases to be completed with minimal human intervention. Currently, each phase is saved and stored separately, handing off files between each phase; this process will ideally be streamlined to reduce the need for additional input and output files and resulting in a unified open-source schema for the complete description of wind blade geometry and properties. In addition to efficiently transitioning between the Blade Machine phases, automation is a crucial consideration for future development of this technology. While matching airfoils are currently selected by the user, as described in this paper, Phase I has been updated with a set of completely autonomous routines that match airfoil geometries to cross sections of noisy point cloud scans. Future developments will apply this and other automation to the subsequent phases, such as processing Phase II interior web information and generating the thick blade model in Phase III.

Blade Machine currently runs with four phases, but the goal of the technology is to incorporate a fifth phase that addresses finite element analysis. By integrating FEA into the Blade Machine process, the technology will generate more than a visual twin of the actual blade but a digital twin model that also contains information about the structural properties of the blade. This will further aid in designing reuse potentials for wind blades that are technically assured.

4 CONCLUSIONS

In the face of global climate change, there have been increasing multinational actions taken to mitigate greenhouse gas emissions by utilizing clean energy. Growth in the wind power industry is seen globally, as more countries and regions pledge to increase their proportion of wind energy in relation to carbon-intensive energy sources (Dyrholm 2021). Along with this increase in adoption of wind energy, the technology of harnessing wind energy is advancing and leading to larger, more efficient wind turbine blades (Lefeuvre 2019). These technologies are greening our world's energy mix, but full sustainability in the wind energy industry will depend on the ability to re-use materials and structures from obsolete wind turbines in meaningful applications.

The work of recapturing the geometry and materiality of wind turbine blades, as reported in this paper, is just one instance of a methodology to recreate models and data for many items in civil infrastructure, which when decommissioned create vast volumes of waste from once valuable structures. We imagine a future where objects such as precast concrete elements, structural steel shapes, mass timber floors and walls and other structures can be creatively re-purposed, instead of demolished or downcycled. The Blade Machine technology reported on in this paper will be a key technology in realizing this vision.

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