From blades to tracks: a case study in structural reuse of curved surfaces for circular design

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Figure 1: Our prototype pumptrack module (seen on the left hand-side of the picture) being tested by a BMX rider. Our module is made of two panels extracted from a decommissioned wind turbine blade, and matches the curvature of standard modules (seen on the right hand-side). Picture by ©Patrick Wetzels, TU Delft.

Abstract

We explore the fabrication of curved surfaces by reusing panels extracted from decommissioned wind turbine blades, using cycling pumptracks as a case study. We first present real-world prototypes of pumptrack modules that we manufactured to evaluate the practicality of this reuse scenario and to define the boundary conditions for harvesting blade panels and assembling a track. We then propose an algorithm to optimize the segmentation of a wind turbine blade into quadrilateral panels whose sides fall within a small set of compatible boundaries. These panels form a library of modules that designers can connect side by side to create pumptracks of various lengths and curvatures. Together, these contributions provide a proof-of-concept of how computer-aided design and manufacturing can support circular design through the reuse of curved surfaces.

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Keywords

Circular design, structural reuse, shape segmentation, wind turbine blade, pumptrack

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1 Introduction

The current global production and consumption system has adverse impacts on the earth's ecosystem. In particular, the construction sector and the energy sector are two major contributors to climate change, resource depletion and waste generation. On the one hand, the construction sector needs large volumes of raw materials and is responsible for a substantial proportion of CO2 emissions [United Nations Environment Programme 2024]. On the other hand, while wind energy is renewable, wind turbine blades are made of composite materials that are hard to recycle, and are often landfilled or incinerated once decommissioned. Studies anticipate that wind turbine blades will result in a cumulative waste of tens of million tons by 2050 [Liu and Barlow 2017].

The circular economy aims to reduce or even eliminate environmental impacts by closing resource loops through reuse and recycling. Our goal is to form such a loop between the energy and construction sectors by reusing wind turbine blades as construction elements. *Structural reuse* is a recovery strategy that consists of cutting products into reusable segments [Fivet and Brütting 2020; Joustra et al. 2021a]. This approach is especially relevant for products that are hard to recycle or reuse in their original form, such as the high-grade fiber-reinforced polymers used in wind turbine blades [Jensen and Skelton 2018; Li et al. 2025]. Although segmentation discards the original product function (in our case, turbine blade), it retains the inherent material value and much of its structural quality. Being decommissioned for economic or legal reasons [Tazi et al. 2019], the blades are often still in sound physical condition when dismantled.

Prior work in design and architecture has focused on the reuse of beams and joints between them to create truss structures [Amtsberg et al. 2020; Brütting et al. 2019], or flat panels to create furniture [Joustra et al. 2021b]. In this paper, we explore the reuse of *curved surfaces* to create other surfaces. Targeting curved surfaces raises unique challenges for design and fabrication, both in identifying shapes that can be achieved through reuse, and in manufacturing these shapes from reclaimed products.

We tackle these challenges by combining expertise in industrial design and in digital modeling and fabrication. Specifically, we adopt a research-through-design methodology, where we develop a real-world product to define the design process and its parameters, and subsequently implement a computer-aided design tool informed by the practical experience gained through this case development. While our work is motivated by applications in the building industry, we conducted our study by designing *pumptracks*, which are bike tracks made of bumps of various heights and lengths that cyclists ride by inducing momentum through up and down movements of their body. Pumptracks can be composed of mobile modules (Figure 1), or be constructed as permanent installations (Figure 2). We observe that the curvature of pumptrack rollers and turns aligns well with the curvature of wind turbine blades, making them good candidates for design by reuse. In addition,

Figure 2: Pumptracks can feature rollers and corners of varied curvature, making them a rich object of study for shape design.

tracks are essentially 1-dimensional objects, making their design an easier starting point than 2-dimensional facades or roofs. Still, pumptracks must satisfy specific requirements on surface continuity and smoothness related to user experience, safety, and assembly, which serve as effective boundary conditions for developing a computer-aided design tool.

In this paper we detail our developed workflow and lessons learned during the design and fabrication of mobile pumptrack modules made of wind turbine blades. We describe our panel selection process for creating a continuous track, our cutting and assembly methods, and how we evaluated the resulting track with practitioners (Figure 1). We then introduce an optimization algorithm to automatically segment a wind turbine blade into a modular set of panels with continuous boundary connections, allowing designers to quickly create various tracks by chaining compatible modules, akin to arranging dominoes (Figure 13). We end the paper by discussing the extension of our approach and algorithm to architectural surfaces.

2 Related work

Researchers have considered building architectural structures with reclaimed beams and panels (slabs) of various material origins, including concrete and concrete rubble [Grangeot et al. 2025; Küpfer et al. 2024; Pekuss and Popescu 2024], steel [Brütting et al. 2019; Favilli et al. 2025; Van Marcke et al. 2024], wood [Amtsberg et al. 2020; Yoshida et al. 2019], and even plastic bottles [Kovacs et al. 2017] or skis [Colabella et al. 2017]. In many cases, prior work confined the reused elements to the same domain as their original purpose, i.e., reusing reclaimed building elements to create new buildings. In contrast, we explore reuse between two different domains – wind energy and construction.

Wind turbine blades have been a popular case for repurposing and structural reuse as they present a challenging and pressing recycling problem, but also an aesthetically interesting object. Repurposing aims at minimizing material processing and maximising the use of the blade as-is. It uses design principles such as repetition and takes advantage of the blade's elegant aerodynamics to create aesthetically pleasing sculptures, such as the shelters by BladeBridge [2025], playgrounds by SuperUse studios (Figure 3) and design explorations by the RE-Wind project [Re-Wind 2025].

Figure 3: The Wikado playground by SuperUse studios, Rotterdam, illustrates how wind turbine blades can be creatively repurposed as construction elements.

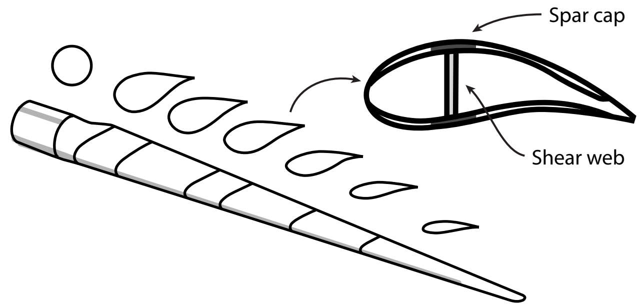


Figure 4: Typical wind turbine blade design, illustrating multiple airfoil profiles, twist and linear taper (left). Internally, the blade is strengthened by a shear web connected to glass fiber spar caps on each side (right).

Although at present repurposing is often characterized by local, occasional solutions, work is also underway to develop functional, structural and scalable applications [Infrablades 2025]. However, the peculiar shape of wind turbine blades limits the range of objects that can be created solely through repurposing.

Structural reuse aims for greater diversity of outcomes by segmenting the reclaimed product into reusable elements. Joustra et al. [2021b] explored this strategy by extracting flat panels from wind turbine blades, within the curvature tolerances of construction standards. Pronk [2022] proposed an approach to map trade-standard panels onto a 3D blade model, while Kik [2024] assigned a triangular mesh pattern to obtain elements for constructing a geodesic dome. These approaches eliminate the shape complexity in reuse by harvesting construction panels with known geometric and mechanical properties. This approach could increase the scale of reuse, but requires more processing (sawing) and ignores the opportunities for using the distinct curved shapes functionally. Another approach involves Circular Applications Through Selection Strategies [Carrete et al. 2023], which systematically links material and geometric properties to potential uses across multiple life cycles. This design method emphasizes identifying a subsequent use scenario, which is then developed based on the resulting requirements.

In terms of determining an appropriate segmentation strategy, a number of computational approaches have been developed in an architectural context. Given a stock of reclaimed elements, digital tools have been proposed to optimize cutting and assignment of the elements to best reproduce a target structure, which can be solved using diverse algorithms, including genetic optimization and mixed-integer programming [Huang et al. 2021; Tomczak et al. 2023]. Recent work in computer graphics optimizes reuse of curved surfaces by leveraging local shape descriptors to identify promising assignments [Baas et al. 2025], or by working on flattened, quantized panels for garment reuse [Qi et al. 2025]. The algorithm we propose differs in its goal, as we aim at extracting modular panels that can be combined to form diverse structures rather than optimizing custom panels to best reproduce a specific structure. Our work also relates to algorithms for approximating shapes with standardized elements that can be mass produced, typically by representing the surface as a mesh whose nodes, beams, or panels fall into a small number of classes [Brütting et al. 2021; Chen et al. 2023; Eigensatz et al. 2010; Fu et al. 2010; Liu et al. 2024; Qiu et al. 2025; Singh and Schaefer 2010; Xiong et al. 2022; Zimmer and Kobbelt 2014]. But while these methods cluster and optimize the shape of construction elements to reduce manufacturing cost, our goal is to optimize the segmentation of a wind turbine blade to best reuse its prescribed curvature.

3 Pumptrack design case study

We conducted a design case study to identify the parameters and workflow for structurally reusing wind turbine blade segments. We focus on creating straight rollers for a modular pumptrack that can be assembled in various configurations and different locations. We chose this particular type of module because we observed that the sinusoidal shape of rollers can be well approximated by connecting two S-shaped blade panels. A 30m long end-of-life wind turbine blade was used for full-scale prototyping. The project followed a process of quick prototyping and evaluation cycles to verify assumptions and define design parameters. The design process followed a double diamond approach with four stages: discover, define, develop and deliver [Council 2025]. First, we *discovered* the available stock and reuse scenario, which informed *definition* of the design parameters for both wind turbine blade processing and pumptrack design. Then, we iteratively *developed* the segmentation strategy to extract the panels and *delivered* the modules for building and testing the prototype. We tested the 1-1 pumptrack prototype during a one-day test event (Figure 1).

3.1 Case study definition

Wind turbine blades. The design of a wind turbine blade results from a combination of aerodynamic and structural requirements. The outer shape of the blade is determined by a succession of airfoil profiles [Joustra et al. 2021b; Resor 2013]. Their chord length, thickness and twist with respect to the longitudinal axis decreases towards the tip (Figure 4, left). When zooming in on the blade cross section, the integration of aerodynamic and structural design becomes more apparent (Figure 4, right). The spar caps, made of solid glass fiber or carbon fiber composite provide longitudinal stiffness to the blade, the shear web in between transfers loads and

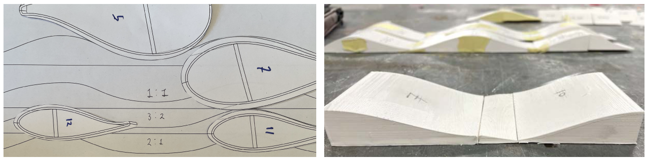


Figure 5: We used paper prints of blade cross-sections to find potential matches with pumptrack rollers of different curvature (left), and virtual and 3D-printed modules to verify continuity at connections (right).

prevents collapse. The shells on the leading and trailing edge, made with a lightweight sandwich structure, complete the aerodynamic profile. Like the shape, the material thickness tapers towards the tip, optimizing the strength to weight ratio.

Pumptrack modules. Pumptracks come in many variations and sizes, their design is typically based on local resources, design guidelines and personal preference. They consist of three types of shapes: rollers (the bumps), corners (often angled), and transition pieces that connect them. Rollers typically have a length of 3 to 4 m. and a 1:10 ratio between crest and trough [McCormack 2019]. This ratio can be adapted to define the riding characteristics. Short and steep rollers can feel stiff but help to accelerate, while long and gentle rollers allow a smooth ride and maintaining speed. In addition, skatepark and playground standards dictate a maximum gap of 5 mm. at joining edges and the application of antiskid layer for safety [NEN 2008, 2019]. Thus, the modules need to be designed to provide good surface continuity for a pleasant riding experience, and close matching edges to warrant safe use. Those characteristics form the parameters for matching the curvatures of the blade to the curvatures of the pumptrack.

3.2 Matching process

Throughout our design iterations, we manually matched the pumptrack to the blade in two stages. First, we visually compared 2D cross-sections to identify potential matches in curvature between the blade and a pumptrack roller. Then we prototyped the selected blade segments into scaled track segments to test the assembly.

In 2D, 1:20 scale paper prints proved a quick verification method to identify shape similarities between blade cross-sections and roller ratios (Figure 5, left). To optimize the number of harvestable panels and facilitate track design, we defined 3 module sizes: Small found at the tip, Medium in the middle, and Large at the root end of the blade. We manually evaluated the alignment and measured edge compatibility of multiple modules using virtual 3D models, as well as physical models of scaled 3D-printed modules (Figure 5, right). The inherent blade curvature led to minor misalignment between mated edges. The blade twist and taper was more noticeable, causing vertical misalignment of adjacent rollers. Over a length of 3m this resulted in a cumulative offset of approximately 10 cm with respect to the horizontal plane. We addressed this offset by using height-adjustable supports, as shown in Figure 7c. Twist is unlikely to negatively affect usability, as such shapes are considered making a track fun and exciting to ride [McCormack 2019].

3.3 Prototyping

Figure 6b illustrates the procedure for marking the cutting pattern on the blade surface. We used a jig replicating the desired curvature and arc length of the roller to align the cut by matching it to the blade's curvature. Once aligned, we marked the roller start and end points, using the distance from the spar cap as a reference for drawing the cutting lines. The spar caps and shear web are the only relatively straight parts of the blade and thus provided a reliable reference. The prototype blade had remained uncoated for research purposes, making the spar cap visible through the glass fiber skins, which facilitated accurate alignment.

Cutting blade material requires specialized equipment because of its toughness, shape and the dust being released in the process. Available technologies range from excavator-mounted circular saws for large, straight cuts, to handheld jigsaws for small, curved cuts on thin-walled parts [Lund et al. 2023]. For this study, the blade was roughly cut into 1.5m wide segments on-site (Figure 6a), followed by extracting smaller panel elements using a handheld circular saw. We made the final, precise cuts using a flatbed CNC waterjet cutter (Figure 6c). We prefer waterjet cutting for its accuracy, but also because the glass fiber dust is immediately collected in the run-off water. The cutting angle affected the gap at the joining edge. A cut perpendicular to the top surface produces a perfect edge alignment. However, we slightly over-angled the cuts, creating a V-groove on the inside to tolerate minor misalignments without affecting the riding surface. For the flatbed CNC machine with 3 degrees of freedom (linear xyz) used in this study, the panel had to be lifted at one end to achieve the desired cutting angle.

From the available material we cut 2 Large modules (1554 mm. long, 1:10.2 ratio) and two Small modules (1075 mm., ratio 1:7). The segments weighed between 33 and 64 kg, the weight difference being caused by the ratio of spar cap and sandwich material present in the modules. On average, our modules made from blades have a lower weight (57 kg) than conventional pumptrack modules (62 kg). We connected the modules using angle brackets (50x50x3mm) clamped to a square tube support (40x40x3) using an M10 bolt (Figure 7, left). Partial inserts and threaded rod (M8) with washers clamped the angle bracket to the bottom of the riding surface. Using partial inserts prevented fasteners obstructing the riding surface and allowed dismantling, separation and reusing individual parts. For each module, we positioned the M10 bolts 45mm below the riding surface to compensate for variations in material thickness, thus securing a smooth connection between the modules. The twist of the blade panels was accounted for by using ball bearing feet with individual height adjustment (Figure 6, right). A brace between the leg and the angle bracket enabled aligning the legs perpendicular to the ground surface (figure 7b). Safety precautions such as an anti skid coating and load verifications were applied [NEN 2008, 2019].

3.4 Testing

We tested the pumptrack modules with a live event on our university campus. A local company supplied a mobile, modular pumptrack for one day, to which we connected our modules. The track was laid out as two parallel straights of approx. 20m, with the prototyped blade rollers connected at the end (Figure 8). We added a plywood ride-out to absorb the twist-induced offset and ensure a smooth exit

(a) On-site segments (b) Jig to trace panel boundaries (c) Waterjet cutter (d) Final assembly

Figure 6: Processing the wind turbine blade: cutting into segments on site (a), marking the panel boundaries with a curved jig (b), cutting the panels with a CNC waterjet (c), placing the resulting module on a track (d). Picture (a) by ©Fraunhofer IWES.

(a) Connection (b) Angle bracket (c) Adjustable foot

Figure 7: We designed custom connectors to join blade panels of varying thickness (a). The panels are connected through angle brackets (b) and supported by adjustable feet (c).

Figure 8: Setup for the pumptrack test event: two parallel tracks, the final rollers made with wind turbine blade panels. Picture by ©Patrick Wetzels, TU Delft.

from the track. Both tracks required at least 2 people to build. The blade modules took longer to assemble than the conventional track, using bolts instead of slotted connections. The connections closely mated the joining edges and ensured a flush ride. The modules performed as expected under cyclic loading. We visually inspected the track during use, but observed no significant deformation, delamination, or surface degradation, confirming that the material provided sufficient compressive strength and resilience to dynamic loads. However, we set the blade modules up to the same height as the conventional track (38 cm), higher than the originally designed 30cm, resulting in a roller ratio of 1:6 (Small sized roller) and 1:7 (Large sized roller).

Approximately 50 participants rode the track, of which 15 filled out a survey and 5 were interviewed for their experience. Around 60% of the participants had no prior experience with riding a pumptrack, but the general experience was positive, resulting in an average score of 4.2 out of 5 points. In scoring their perception of the blade roller on a 5-point Likert scale (Figure 9), the participants agreed that the blade roller was safe, stable and provided good grip to the surface. However, they also perceived the blade modules as relatively stiff and steep, which was also recognized in the interview; *"When placing too many of these relatively short rollers in series, the track could feel a bit stiff"*. This sensation was likely caused by the rollers being set up too high during the event, giving them a *"jumpy"* and slightly *"pointy"* characteristic. Short rollers require faster, more skilled pumping motions, particularly when placed at the end of the track where rider speed is highest. According to track

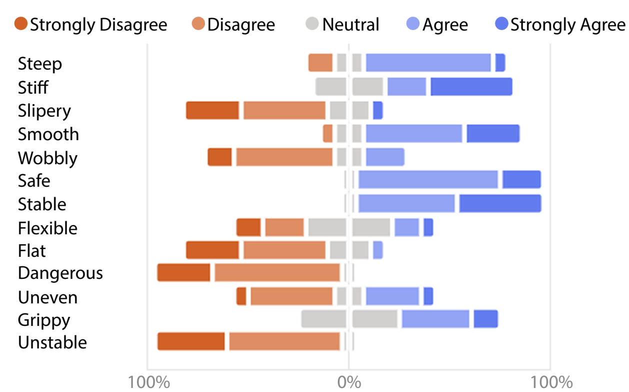


Figure 9: Summary of participant answers to our survey about their perception of the blade rollers.

supplier, who managed the event, the prototyped modules *"held up perfectly"*, demonstrating structural integrity and resistance to impact forces, considering them *"a fun, sustainable alternative to current modules."*

The blade segments proved a good match to pumptrack rollers. The blade shape had a direct effect on the track, defining the height-length ratio of the rollers and introducing a twisting effect. We recommend using these blade characteristics to shape the track's riding experience, e.g. by varying roller layout to create smooth and exciting runs, using the twist to lead into corners or to create an undulating track (Figure 13). We also found the cutting approach to be applicable to a 60m blade model, twice the size of the blade used for prototyping. Manual matching revealed a consistent height-to-length ratio for the rollers, scaled proportionally with blade size.

4 Synthesizing a kit of pumptrack modules

Our design case study showed that curved panels cut from wind turbine blades can be assembled into pumptrack modules. But identifying panels that connect continuously required tedious trial and error with virtual and physical models of the blade, despite focusing on a single type of straight roller. Informed by this demonstrator, we now introduce an algorithm to automatically place cuts along segments of a wind turbine blade to form a more diverse set of modules that can be combined to create pumptracks with varying curvature and twist. We first describe our algorithm to extract these modules, and then explain how to chain these modules to form long, continuous tracks.

4.1 Optimizing cuts for geometric continuity

We frame our optimization as a discrete selection problem. Given a set of panels of wind turbine blade, we first generate multiple candidate cuts over each panel. We then select two cuts per panel such that the resulting modules have maximal geometric continuity across their boundaries, ensuring that they can be connected seamlessly.

Cut parameterization. The input to our algorithm is a set of panels of a wind turbine blade, similar to those used in our case study. In our experiments, we create these panels by cutting a virtual model of a blade into 1.5 meter wide segments, and by subsequently cutting each segment into 4 panels corresponding to the top and bottom parts of the blade, separated by the spar cap, as shown in Figure 10(a-c). Then, we parameterize the planar cuts over these panels by varying the distance t and angle θ of a vertical cutting plane with respect to the spar cap. We generate evenly-spaced cuts by placing the cutting planes 0.1m apart (including the start and end of the panel) and by rotating them according to five orientations within $[-\pi/16, +\pi/16]$. As a final refinement, we discard the candidate cuts that do not cross the blade panel from side to side, in the direction of the spar cap. Two cutting plane candidates are shown in Figure 10(d).

Cut optimization. We denote $\mathcal{P}$ the set of input blade panels, and $\{c_k^P\}$ the set of candidate cuts generated over a given panel $P \in \mathcal{P}$, to which we associate binary variables $\{\mathbf{c}_k^P\}$ that equal 1 when a cut is selected in the solution, 0 otherwise. We limit the number of cuts to 2 per panel, which we impose with a constraint:

$$\sum_{k \in [1, K-1]} \mathbf{c}_k^P = 2. \tag{1}$$

Additionally, we impose that the first and last cuts of a panel are always selected by setting their respective variables c_0^P and c_K^P to 1. With this setting, the optimization yields 3 modules per panel.

Our goal is now to select cuts such that each module can be seamlessly connected to as many other modules as possible. To reach this goal, we first define a binary function $\delta(c_i^A, c_j^B)$ that indicates if two modules A and B are compatible along cuts c_i^A and c_j^B:

$$\delta(c_i^A, c_j^B) = \begin{cases} 1 & \text{if } f(c_i^A, c_j^B) \leq \epsilon \,, \\ 0 & \text{otherwise,} \end{cases} \tag{2}$$

where the function $f(c_i^A, c_j^B)$ measures the geometric continuity of the surface obtained by connecting modules A and B along the cuts, and ϵ is a threshold on how much discontinuity is tolerated, which can be adjusted according to the targeted usage scenario. We then optimize the cut selection to maximize the number of compatible connections between any pair of modules:

$$\underset{\{\mathbf{c}_k^P\}}{\operatorname{argmax}} \sum_{(A,B) \in \mathcal{P}} \sum_{c_i^A} \sum_{c_j^B} \mathbf{c}_i^A \mathbf{c}_j^B \delta(c_i^A, c_j^B). \tag{3}$$

In our experiments, we define $f(c_i^A, c_j^B)$ to measure continuity in position, orientation and curvature. Specifically, we extract the curves formed by the cuts along the surface of each panel and we sample each curve at evenly-spaced points. At each sample point, we compute the Darboux frame (curve tangent t, surface normal n and binormal b) and the surface normal curvature κ in the direction of the binormal. Given two cuts c_i^A and c_j^B, we first register their sample points via Procrustes alignment of their Darboux frames. We then compute the residual misalignment of each pair of corresponding frames as the mean absolute value of their vectors dot product. We complement this measure with the difference in normal curvature, yielding:

$$\begin{aligned} f(c_i^A, c_j^B) = \frac{1}{S} \sum_{s=0}^{S-1} & |\kappa_i^A(s) - \kappa_j^B(s)| \\ & + \left(|\langle t_i^A(s), t_j^B(s) \rangle| + |\langle n_i^A(s), n_j^B(s) \rangle| + |\langle b_i^A(s), b_j^B(s) \rangle| \right)/3. \end{aligned} \tag{4}$$

Equation 4 assumes that the two cuts to compare have the same number S of samples. When this is not the case, we test all possible placements of the shorter cut along the longer one in a sliding window fashion, and retain the placement that minimizes Equation 4. Furthermore, since a cut separates the panel into two parts, we also need to test whether the same sides of two cuts can be connected after rotating one of the panels by 180°, i.e., after bringing the left part of one cut to the right of the other cut, and vice-versa. In practice, we can account for this rotation by traversing the point samples of one of the two cuts in reverse order before performing registration and evaluating Equation 4.

Finally, we impose additional constraints to prevent the selection of intersecting cuts and to ensure a distance of at least 60% of the total panel length between consecutive cuts. We implement these constraints by identifying invalid pairs of cuts in a pre-process step, and setting $\delta(c_i^A, c_j^B)$ to zero for these pairs.

Figure 11 illustrates the benefit of this optimization on a typical pair of panels, where the optimized cuts prevent gaps and surface discontinuity compared to arbitrary cuts.

Implementation details. We implemented the optimization as an assignment problem using Google's OR-Tools framework [Perron and Furnon 2025]. In this context, we define a binary variable $\mathbf{c}_k^P$ for

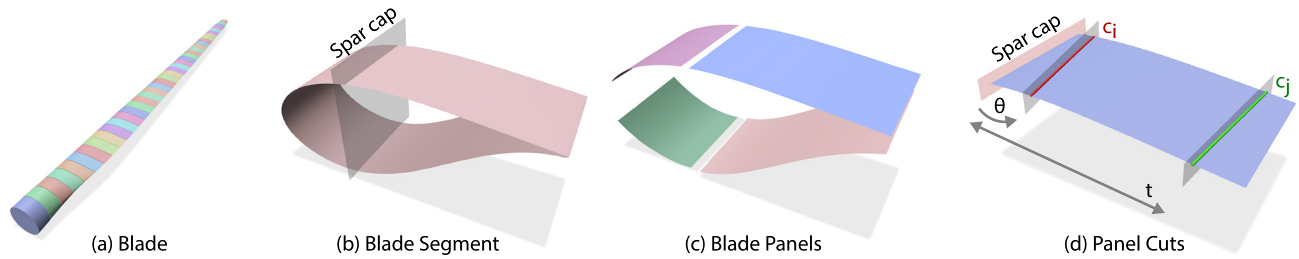


Figure 10: Given a blade model (a), we divide it into 1.5 meter wide segments (b). Each segment is then separated into 4 panels by splitting the top and bottom parts of the model along the spar cap (c). For each panel, we parameterize cuts $\{c_i\}$ by the distance t and the angle θ with respect to the spar cap plane (d).

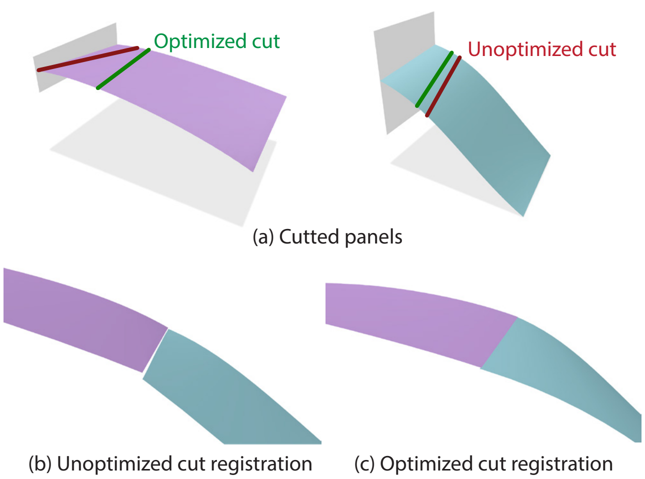


Figure 11: The twist and taper of the blade can yield visible gaps and curvature discontinuities between panels when cuts are placed arbitrarily (a & b, red cuts). Optimizing the cuts allows a continuous connection (a & c, green cuts).

Table 1: Runtimes (in seconds) for an increasing number of panels. For each setting, the pre-computation time includes the detection of invalid cuts and the pair-wise compatibility evaluation, while the solving time corresponds to the assignment problem.

Nmbr. of panels	Pre-computation (s)	Solving (s)
12	6502.2	21.3
24	21944.5	135.4
48	133899.1	1980.2

each candidate cut k on panel P and model the multiplicative term $\mathbf{c}_i^A \mathbf{c}_j^B$ in Equation 3 through the definition of a boolean variable $z[A, B, i, j]$ that behaves as the logical AND operation between the two single variables. We pre-compute $f(c_i^A, c_j^B)$ for all pairs of cuts, and read them from a look-up table while defining the objective function. Table 1 reports the runtime (in seconds) of pre-computation and solving for an increasing number of panels. The current bottleneck resides in the pre-computation of $f(c_i^A, c_j^B)$ for all valid pairs of cuts, which is implemented sequentially in our prototype while it could be easily parallelized. Although the overall computation time scales rapidly with the number of panels, solving the assignment problem only takes around 20 seconds for 12 panels, up to 30 minutes for 48 panels, considering an average of 65 cuts per panel.

4.2 Creating tracks from extracted modules

Given the modules extracted by our optimization, designers can create long tracks one module at a time, starting from any module and selecting the next module from the list of modules having a boundary compatible with one of the two extremities of the track. To ease this workflow, we additionally propose an algorithm to label groups of compatible boundaries, such that each module has one label at each of its extremities, akin to domino pieces. Displaying these labels as colors allows designers to quickly identify compatible modules, and to plan the track several modules ahead.

Boundary clustering. Our goal is to identify, among the set of modules created by the above optimization procedure, subsets of modules that share a compatible boundary. To do so, we first build a graph where each node represents one of the two boundaries of a module and two nodes are connected by an edge if the corresponding cuts are compatible, as indicated by $\delta(c_i^A, c_j^B)$. We then identify all fully-connected subgraphs by running the Bron–Kerbosch algorithm [1973] and extracting the non-overlapping subgraphs by order of size. When the algorithm leaves some nodes alone, we assign them to the subgraphs with which they share the strongest connections, as measured by Equation 4. While this last step might group boundaries that exceed the tolerance threshold, it offers designers greater options for reconfiguring the modules. Figure 12 illustrates this clustering on a simple example, which results in three boundary labels that we color in red, green and blue.

The cut optimization presented in Section 4.1 aims at favoring compatible boundaries between modules, which in turn should yield tighter clusters of boundaries. We validated this hypothesis by running the clustering algorithm on a set of 72 boundaries extracted from 36 panels, using either random cuts or optimized cuts. Using optimized cuts results in 6 clusters and 26 isolated boundaries, while using random cuts results in 2 larger clusters but 37 isolated boundaries. Moreover, the clustered boundaries obtained from optimized cuts exhibit a smaller average pairwise residual misalignment compared to the ones obtained from random cuts.

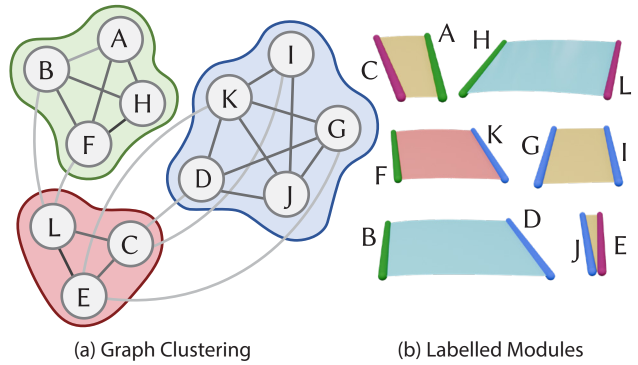
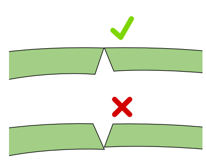


Figure 12: We cluster groups of compatible panel boundaries by building a graph where nodes represent boundaries and edges connect compatible boundaries. We identify the relevant groups by extracting the non-overlapping, fully-connected subgraphs (a). We assign a different color to each group to visually identify compatible modules (b).

Track assembly. Equipped with boundary labeling, users can quickly explore track layouts by chaining module along boundaries of same colors. For each pair of consecutive module, we perform Procrustes alignment between the boundary sample points, accounting for the 180° rotation around the module's vertical axis when needed. Once the track is complete, we manually rotate it to place it on the ground. Figure 13c shows a few pumptracks created with this procedure, reporting the actual blade segments extracted from the original model in Figure 13a and the optimized modules with color-coded boundaries in Figure 13b. These results illustrate how one can leverage the curvature and twist of the wind turbine blade to create diverse tracks with varying rollers and turns. Finally, Figure 14 showcases a different application scenario, where we used our tool to create an arch composed of 4 blade panels, and repeated that arch to form a bus shelter.

4.3 Limitations



Our optimization (Section 4.1) only considers vertical cutting planes and ignores the bevel produced by the plane when cutting the thick blade shell. While our connectors can join panels with non-parallel sides, it is preferable that the resulting V-groove appears on the inner side of the track to preserve surface continuity (inset, top). Future work could integrate this requirement by including the cutting plane tilt as an additional variable to optimize, and the V-groove orientation as an additional test in Equation 2.

The tracks shown in Figure 13 were created by manually selecting a sequence of modules sharing compatible boundaries. Future work could consider developing an optimization algorithm to select from the library of modules the sequence that best reproduces a target track. Various optimization objectives could be considered to not only maximize track smoothness but also to achieve a desired curvature of rollers, or to minimize accumulated twist.

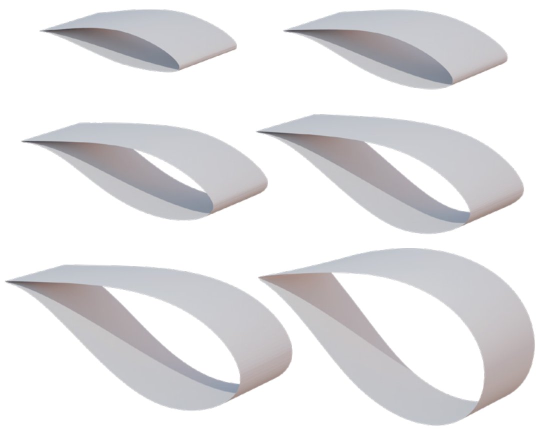
5 Conclusion and Future Work

We have presented a design case study and accompanying optimization algorithm for the harvesting and functional reuse of curved elements from an existing structure. The blade and pumptrack provided a relevant, realistic, safe and fun application for this proof of concept. The physical prototype confirms the practicality of this reuse application, and the developed algorithm expands the range of tracks that can be designed from wind turbine blade panels in a modular fashion.

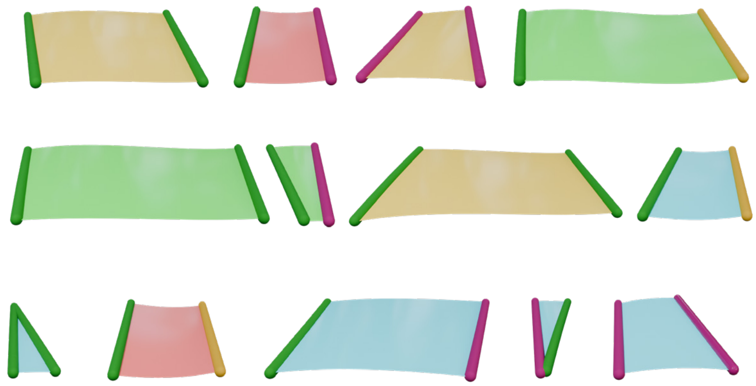
The objective of this study was to cut pumptrack modules from an existing wind turbine blade, focusing on replicating the curvatures of the roller modules and ensuring continuity between adjacent modules. In future, an additional objective could be to maximize reuse, i.e. enlarging the surface area of materials to be cut from the blade. This could be realized by adapting the track design as well as the cutting approach. For example, a quick verification indicated that narrowing the track to 1.10m allows fitting more modules in the same blade, thereby increasing the harvested area by 30 percent. From an algorithmic perspective, additional terms could be introduced to minimize leftover waste when selecting cuts over each blade segment.

The proposed methodology could be expanded to other source materials and reuse applications. In addition to various models of wind turbine blades, the approach could be applied to recover reusable construction elements from end-of-life boats or aircrafts. Being made of composites or high-end aluminum, these structures are hard to recycle [Lefeuvre et al. 2017], and obtain their performance by integrating material composition and (curved) shape. Reusing such elements would preserve their unique properties for a relatively small processing effort while substituting the need for virgin raw materials.

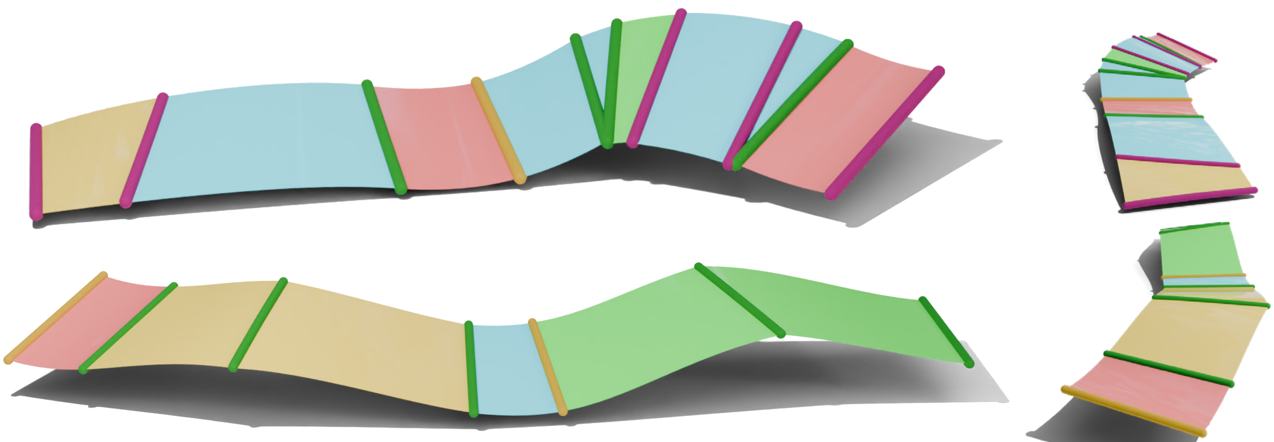
Future applications could include architecture or sports equipment, extending the use to e.g. flooring, walls or roofing systems. Buildings are often made of materials that need to withstand dead loads, live loads and be durable. Traditional materials include concrete, wood, and steel. One avenue for the construction industry to mitigate their contribution to global greenhouse gas emissions is by designing materially-effective buildings. These often have doubly-curved and rib-stiffened geometries that may be difficult to manufacture. Composite materials have good properties for the building industry but are rarely used because of cost. Moreover, they have high embodied energy. Therefore, reusing composite parts has the potential to lower manufacturing cost and their low weight could reduce the overall environmental impacts associated with transport and installation [Beukers and van Hinte 2020]. As such, wind turbine blades present an opportunity for reuse in construction as they offer great strength-to-weight ratios and durability. When repurposed for construction applications, their weather resistance and lightweight properties could make them particularly valuable for large-span structures where traditional materials would require larger cross sections and supporting structures. They could also be segmented into structural elements for (barrel vaulted) floors, cantilevering beams and columns. Finally, they could also be turned into nonstructural elements such as cladding and facade panels (Figure 15) or drop ceilings with potentially acoustic benefit. By



(a) Blade Segments



(b) Modules



(c) Tracks

Figure 13: Taking 6 blade segments as input (a), our algorithm extracts 36 modules and identify 6 groups of compatible boundaries (b, only a subset of modules and compatibility groups shown). The modules exhibit diverse curvature, twist, and angle between their two extremities, allowing to create tracks with corners (c, top) and rollers (c, bottom).

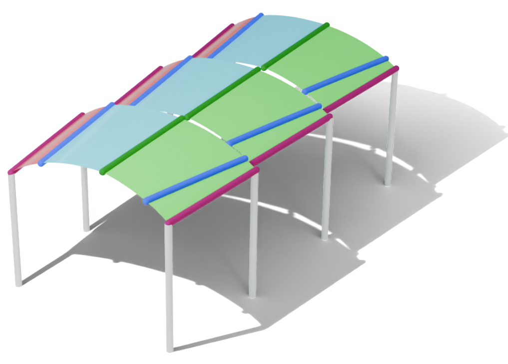


Figure 14: Bus shelter made of 3 arches, each composed of 4 wind turbine blade panels.

Figure 15: Extending our approach to 2D could allow the reuse of wind turbine blade panels for cladding of curved architectural structures (inspirational illustration: roof of Arnhem Centraal station).

diverting these materials from landfills or incineration, the construction industry could significantly reduce waste while capitalizing on high-performance materials that have already completed their primary life cycle, thereby reducing both construction costs and environmental impact [Jensen and Skelton 2018].

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