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Circular applications through selection strategies (CATSS): a methodology for identifying reuse applications for end-of-life wind turbine blades

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Abstract. Wind turbines are crucial for the energy transition, but their end-of-life treatment presents a challenge. Most wind turbine blades, made from composites, are currently sent for disposal or recycled through methods that degrade the value of the material. Structural reuse through blade segmentation was introduced as a recovery method that maintains high material value throughout subsequent life cycles. Most recovery attempts focus on thermoset composites, but thermoplastics are becoming more common. Unlike thermosets, thermoplastics can be reshaped through thermoforming processes, which offers the opportunity of adapting the geometry of a blade to new reuse applications. This paper introduces selection strategies to identify secondary applications of reshaped thermoplastic blade sections. A new methodology is proposed based on Landru's selection strategies and the Material Driven Design method (MDD). The Circular Applications Through Selection Strategies (CATSS) methodology proposes understanding a material at different levels to identify applications. Each sectioning level of the blades yields different material characteristics, such as the reshapability, that are then put into Landru's three selection strategies: substitution, selection by function, and inverse selection. Substitution directly supplants other materials with blades in an existing application; selection by function compares material properties and performance indices to derive the most relevant functions (i.e. "light-weight beams"); and inverse selection identifies suitable market sectors. The CATSS method is a systematic approach to exploring the reuse of blade sections across multiple life cycles, taking into consideration the changes in blade geometry introduced by each sectioning level. For example, the second use cycle might use blade segments for infrastructural applications like electrical transmission poles, while 3rd and 4th cycles reuse blade elements or blade units for urban furniture or automotive parts, respectively. Thus, by identifying multiple use cycle applications at various sectioning levels, we introduce structural reuse and reshaping as a long-lasting recovery pathway for decommissioned wind turbine blades. The selection strategies presented on the one hand can help identify new applications for thermoplastic composite products at their end-of-life, while on the other hand they indicate which aspects need to be considered in the original design, thus contributing to more circular practices in the composites industry.

1. Introduction

Wind turbines are one of the most developed sources of renewable energy, making them crucial for the energy transition. The use of wind energy is expected to grow exponentially in the following decades, as will the waste associated with the production and decommissioning of wind turbines. Liu et al suggest that most of the end-of-life waste of wind turbines is derived from the blades. [1] Wind turbine blades (WTBs) are made from fibre reinforced polymers (FRPs). End-of-life (EoL) options for FRPs are limited due to the complexity of separating its constituents. Beauson et al. identified that the reuse, repurposing, and recycling WTBs are a chain of processes where the blades are transformed into new materials in accordance with circular economy principles [2]. In a circular economy, materials and resources flow while preserving their value by looping back into manufacturing processes at different stages [3]. However, due to the complexity of FRPs, landfilling and mechanical recycling are the two most common EoL strategies for WTBs [2], [4]. Recycling is more desirable than landfilling, but it is also the least favourable within a circular economy because all material functionality is lost [3], [5].

A more favourable EoL strategy is *structural reuse*, which is a process that repurposes (partial) components of a blade in sections that retain the load-bearing capabilities of the original material [6], [7]. Joustra et al. propose a method of segmentation that preserves material integrity while expanding the opportunities of reuse to product categories such as urban furniture [8].

The segmentation method was tested on a case study made from a glass fiber/epoxy WTB. However, recent developments in thermoplastic composites has increased their use in WTBs [9]. Unlike their epoxy counterparts, thermoplastic composites can be reshaped with appropriate thermoforming processes. Thus, the geometry of elements from thermoplastic blades can be adapted to different secondary applications than thermoset WTBs.

The structural reuse of reshaped thermoplastic blades in secondary applications has not yet been explored. There is no comprehensive method for identifying suitable secondary applications, either. We aim to establish such a strategy in this work with the Circular Applications Through Selection Strategies (CATSS) method – a systematic approach to identify structural reuse applications.

The CATSS method combines Landru's selection strategies with Karana's Material Driven Design (MDD) method to identify secondary applications for WTBs. Section 2 introduces the existing methods for finding applications for materials. Section 3 presents the CATSS method in detail. Section 4 then reframes applications from literature under the lens of the CATSS method. The two closing sections discuss the strengths and limitations of the methodology at this stage and its potential impact in promoting structural reuse as an EoL strategy for WTBs.

2. Finding Applications for Materials

Materials are typically chosen for a specific application based on a set of constraints and design requirements [10], [11]. In a structural reuse scenario, the logic is inverted – design applications and requirements are derived from a given material. Landru's selection strategies and Karana's MDD method both use this inverted logic to find applications for materials.

Landru et al. propose three strategies to find applications for materials - substitution, selection by function, and inverse selection [12]. In substitution, a new material replaces one already used in a specific application. Substitution facilitates identifying new applications based on what exists in the market. Selection by function uses performance indices to identify functions for the material. Performance indices are combinations of material properties that can be used as a benchmark when comparing material candidates. Material databases such as Ansys Granta EduPack™ can be used to identify the indices that make a material stand out. The results of this strategy include a set of broadly defined functions such as "light-weight load-bearing structures", which is connected to a quantifiable performance index. Inverse selection identifies suitable market sectors based on material characteristics. With the most relevant market sectors identified, this strategy yields the broadest results of the three.

The MDD method is comprised of four steps that begin with understanding a material and end with developing a material demonstrator that emphasizes the material's unique qualities. Only the first step, *Understanding the Material*, is discussed here because it broadens the focus beyond mechanical aspects and includes characteristics such as aesthetics and material experience.

3. CATSS Method

Finding secondary applications for decommissioned WTBs poses the challenge of starting from a material that has been in service for 20-25 years. The two methods mentioned above are the only ones found that find applications from a material. As such, they were used as the basis for the CATSS method, which combines the two in a manner that is relevant for the context of WTBs by introducing a preliminary step of material sectioning.

Since material properties can change after years of service, it is imperative to first understand the residual properties of WTBs before proposing any suitable applications.[13] The following section present the levels of understanding needed to repurpose blades throughout multiple use cycles.

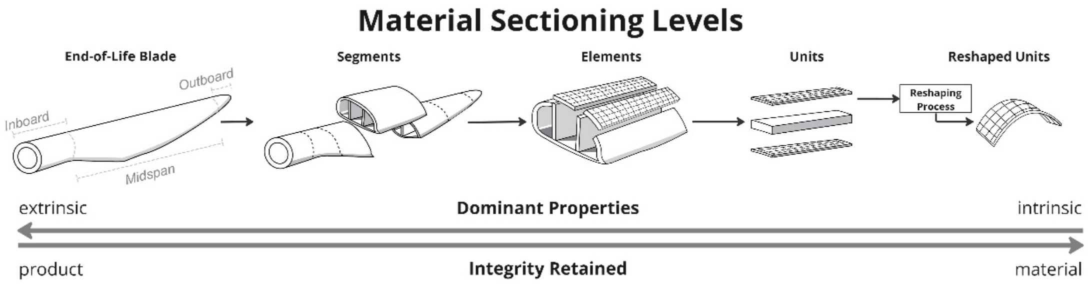

Figure 1 Material sectioning levels for a thermoplastic wind turbine blade

3.1. Material Sectioning

The first step of the CATSS methodology emphasizes the importance of understanding the blades' properties. These properties vary depending on the scale of the sections that are used and their location in the blade, so it is worthwhile to explore the levels of *material sectioning* that can be harvested from a blade.

A decommissioned blade is a macrostructure composed of segments like box-beams (composed of 2 shear webs and 2 spar caps) and an aerodynamic shell. Since the properties of these *segments* change

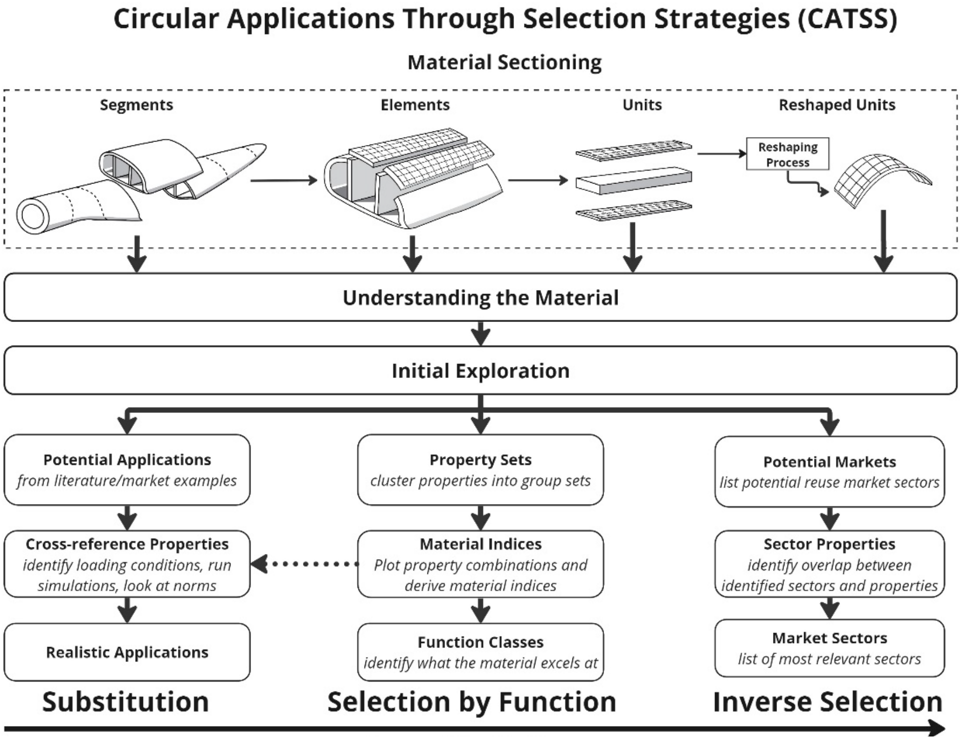

Figure 2 Overview of the CATSS method for identifying material applications

when they are cut, they are governed by dimension-dependent (extrinsic) properties. When these segments are sectioned with longitudinal cuts, they become composite *elements* with different properties. In WTBs, these elements are composed of sandwich structures made from FRP laminates and a core material. When the laminates and core are separated from each other, only the basic *units* remain. Any further separation of the matrix and fibres would lead to recycling rather than structural reuse. The horizontal axis of Fig. 1 shows the gradual changes in material integrity from segments to units, as well as the transition of the dominant properties. Unlike segments, the properties of units are more *intrinsic* and dimension-independent (i.e. density and Young's modulus).[14] Furthermore, the unit sectioning level is where thermoplastic matrices stand out the most because units can be reshaped. The properties of each sectioning level influence which reuse applications are most suitable.

3.2. Circular Applications Through Selection Strategies (CATSS)

The second step of CATSS is an adaptation of Landru's selection strategies. Landru's selection strategies can be used independently or in succession, but they all necessitate some understanding of the material. As such, the CATSS method facilitates the use of these strategies with two preliminary steps – *understanding the material* and *initial exploration*. This is especially important since each sectioning level has different characteristics and properties. Once an understanding of the material is achieved, either one of Landru's selection strategies can be pursued, regardless of sectioning level. Fig. 2 gives an overview of the CATSS method when applied to a decommissioned blade.

3.2.1. Understanding the material. As mentioned before, this step is a reference to the MDD method, which encourages a thorough examination of the qualities and constraints that make a material unique. The examination includes classical characterization methods (i.e. empirical tests, literature research, etc) and "material tinkering", which is an explorative process of creation and evaluation with the material.[15] Tinkering is useful in deriving auxiliary material properties such as aesthetics and materials experience, and yields results that are not only focused on mechanical aspects of the material.

Since the segment sectioning level is governed by extrinsic properties, its characterization requires thorough structural analysis. Alshannaq et al. derived the effective bending stiffness of a Clipper C96 wind turbine blade segment [16]. Joustra et al. used Ansys Granta EduPack's software to derive the properties of construction elements cut out from a reference blade. Since this blade included the layup of laminates, that same information is also suitable to characterize the units level.[8] Table 1 provides an overview of the properties for each sectioning level. The exploratory tinkering process was bypassed by referencing the Re-Wind Design Catalog, in which designers identified the auxiliary properties of WTBs [17].

*Table 1 Mechanical properties of each sectioning level for decommissioned blades (**σ_T** - tensile strength, **σ_c** - compressive strength, and * are actually flexural values)*

Sectioning Level	Size/length	E	G(MPa)	Poisson's ratio	Density	σ_T	σ_C
	m	*GPa*	*GPa*	*[-]*	*kg/m³*	*MPa*	*MPa*
Segments	10 - 20	10 - 27	-	-	-	145-673	145 - 453
Elements	2-10	2-99 *	-	-	300-1650	-	160 - 1330*
Units (GFRP)	-	-	-	-	-	-	-
Unidirectional (UD)	2-10	41.8	26.3	0.28	1920	972	702
Biaxial	2-10	13.6	11.8	0.49	1780	144	213
Triaxial	2-10	27.7	7.2	0.39	1850	700	292
Foam Core	2-10	0.256	0.022	0.3	200	5.6	4.4
CFRP (UD)	2-10	114.5	5.99	0.27	1545	1546	1047

3.2.2. Initial exploration. The overview of mechanical properties and unique qualities of each sectioning level hint at possible uses for the material. The design catalog was used to brainstorm other suitable applications according to the identified properties. This led to the compilation of 60 applications, which act as a primer to think about what each sectioning level has to offer.

The functions of the blade material in these 60 applications were clustered into 11 categories based on the material characteristics that were emphasized in the application. Examples include "chemical resistance", "light-weight", and "load-bearing structures".

Furthermore, the identified applications were categorized according to the market sectors they belong to (i.e. a bridge would be part of "infrastructure"). Here, 16 market sectors were identified in total, but not all sectors were relevant to each sectioning level due to differences in material characteristics. An example of this is explained in Section 4.3. Once these categories are identified, the exploration is complete, and Landru's strategies are employed. The strategies are presented next in order of how specific their outputs are.

3.2.3. Substitution. Substitution is the process in which blades of any sectioning levels replace another material in an existing application. Substitution is composed of three steps: naming potential applications, cross-referencing material properties, and identifying realistic applications. A market analysis and/or state-of-art research into the applications found in section 3.2.2 serve as benchmarks for advances in GFRP reuse. The properties relevant for these applications are cross-referenced with those gathered above to remove anything that is unfeasible. A more elaborate look into the standards and norms of specific applications is appropriate to identify the most realistic applications.

3.2.4. Selection by Function. As a more material-based approach, this strategy consists of three steps: gathering property sets, plotting performance indices, and identifying what the blade sections excel at. Property sets describe combinations of quantifiable properties that, when taken together, describe a function. Recall that the initial exploration stage identified 11 material characteristics. These are composed of relevant material property sets (i.e. density, specific strength, etc). Using a database such as Ansys Granta EduPack, the property sets are plotted into bubble charts that compare various material families. If blade sections outperform other material families within a property set, the corresponding performance index indicates suitable function classes[11]. Alternatively, if the material is close in performance to another material class, then the other material can be used as a starting point for the substitution strategy.

3.2.5. Inverse Selection. The last strategy produces the broadest results. The process consists of identifying potential markets by cross-referencing the material characteristics of a sectioning level with relevant market sectors and evaluating compatibility. Recall that potential market sectors were identified in Section 3.2.2. Each market sector entails specific functions and material characteristics. These properties are cross-referenced with the properties of those of the blade section for compatibility. One way for designers to evaluate the compatibility of a sectioning level with a market sector is by creating a matrix that maps the corresponding market sectors on one axis and material characteristics on the other. Upon each intersection, the relevance of the material characteristic for a specific sector are rated irrelevant to highly relevant (1-5) based on industry knowledge or literature, for example. The sum of all ratings across each market sector is then used to identify the sectors that best emphasize a sectioning level's characteristics. A by-product of this strategy's broad results is that it identifies applications that the other two would miss.

Each selection strategy can be used independently or in conjunction. The CATSS method is a way of exploring a material's compatibility with new applications by deriving relevant criteria, such as material properties, performance indices, and other characteristics relevant to specific sectors.

4. Examples of using the CATSS Method

The CATSS method identifies secondary applications and criteria for feasibility. Despite ongoing efforts to reuse blades, no common approach has been identified. Sections 4.1 and 4.2 take examples from literature that resemble Landru's substitution and selection by function strategies and reframe them under CATSS. The examples illustrate the corresponding strategies as is, but the first two steps of CATSS are added to highlight the advantages of a systematic approach.

4.1. Substitution example. Electrical transmission pole from blade segments

Alshannaq et al. found that WTB segments might be suitable for use as electrical transmission poles because the loading conditions they undergo are similar to those of WTBs in service. Furthermore, FRP poles are entering the market as of late. The compatibility of blade segment properties (identified in a previous step) with those of transmission poles were simulated according to manufacturer data sheets and relevant norms, respectively. The simulations verified that blades abide by the standards used for transmission poles safely. [16] Thus, WTB sections can replace FRP and/or steel poles due to similar loading conditions. The resulting BladePole is an example of substitution, but material data was gathered after finding the application. On the other hand, the first two steps in CATSS gather relevant data beforehand, facilitating the identification of more adequate solutions.

4.2. Selection by function example: Blade element picnic table

Next on the spectrum of specificity, a picnic table was identified as a feasible application for blade elements. To do this, Joustra et al. plotted the flexural properties of blade elements. Figure 3 shows the flexural performance of beams and panels made from materials that optimize performance at minimum mass. The dotted lines correspond to performance indices. For stiffness limited design, the index of $E^{\frac{1}{3}}/\rho$ is used (Fig. 3a). Anything above the line maximizes performance. The recovered blade elements and timber were above this. On the other hand, strength limited design (Fig. 3b) is described by $\sigma^{\frac{1}{2}}/\rho$. The blade elements excelled in this category as well, making them suitable to use in functions that emphasize bending. A picnic table was developed as a demonstrator of this potential. Unlike substitution, the results from selection by function can be applied to any application in which a high specific flexural strength is necessary.

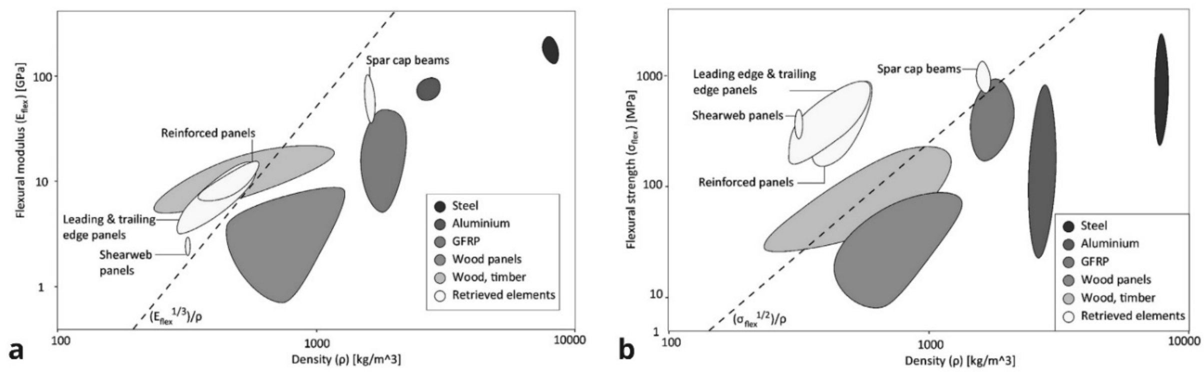

Figure 3 Performance index plots of construction materials for a) stiffness limited design and b) strength limited design (re-printed with the author's permission).

4.3. Inverse selection example: CATSS Exploration

Due to the nature of inverse selection, which yields the broadest results, no concrete examples exist in literature. However, the most suitable market sectors of each sectioning level were already identified during the initial exploration. Taking the segment sectioning level as an example, the affinity between material characteristics and market sectors were evaluated in Fig. 4.

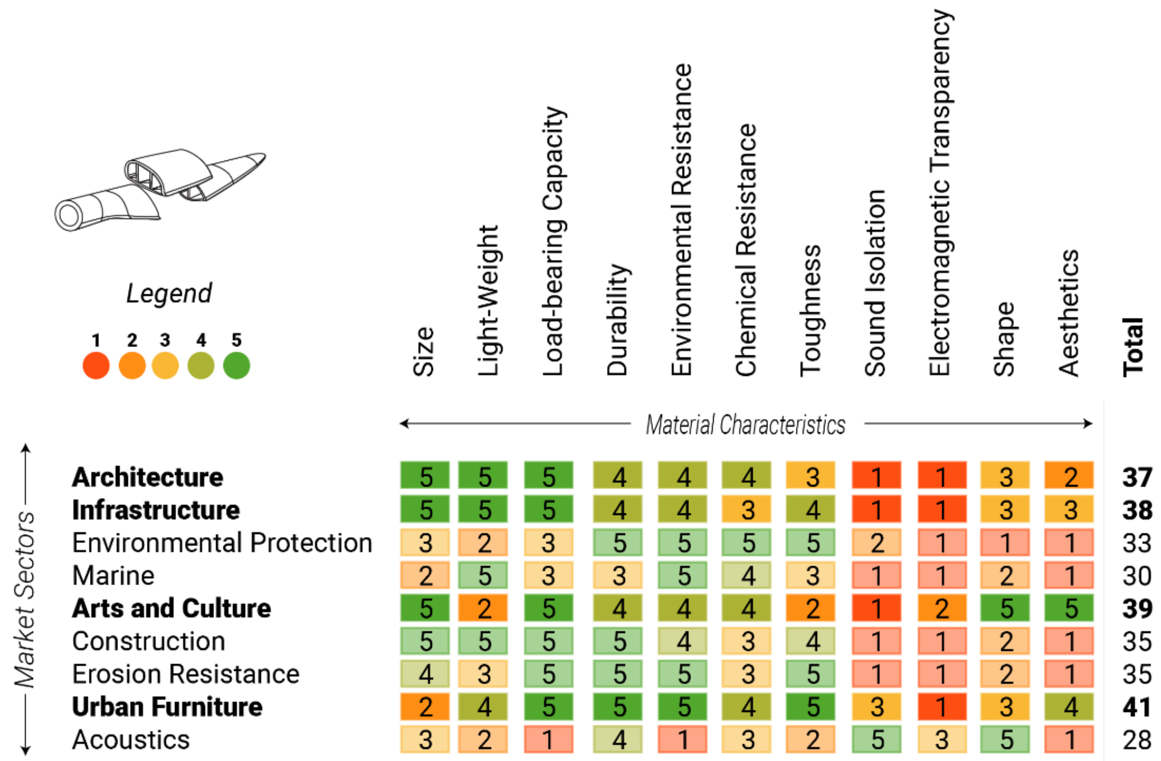

Figure 4 Sample matrix used to evaluate the market sectors for the segment sectioning level. The relevance of each material characteristic for each market sector is rated on a scale from hardly relevant (1) to highly relevant (5).

The numbers in the matrix indicate the relevance of a material characteristic for each market sector. The market sectors with the highest ratings were considered to make the most of a blade segment's properties and are highlighted in the figure. This process was repeated for all sectioning levels. Table 2 summarizes the top markets per sectioning level. Because the results of this selection strategy are the broadest, they showcase the potential of each sectioning level. CATSS provides a way to identify uncommon applications with logic that is based on the material's characteristics.

Table 2 Most relevant market sectors identified for each sectioning level

Most relevant market sectors for each sectioning level	
Segments	Architecture, Infrastructure, Arts and Culture, Urban furniture
Elements	Urban furniture, Infrastructure, Environmental protection, Arts and Culture, Transportation
Units	Interior design, Sports equipment, Consumer products
Units (reshaped)	Automotive, Interior design, Sports equipment, Transportation, Consumer products

5. Discussion

The CATSS method is an exploratory tool to identify secondary life applications for products at their end-of-life. The material sectioning levels identified can be used as successive use cycles that reduce in size each time. The CATSS method encourages a systematic approach to identifying structural reuse applications. The first two steps of CATSS provide a sufficient understanding of the material to explore a broader solution space than what is usually seen in literature. These steps are followed by three systematic selection strategies that open up application spaces.

The CATSS method is still in development, however. Its strength lies in its exploratory nature, but its benefits to look beyond mechanical properties has not yet been fully explored. There are also limitations to using the method, however. Substitution is reliant on obtaining relevant material properties or applications. Selection by function requires access to a detailed database such as the one presented. Inverse selection requires some previous knowledge of market sectors for the evaluation matrix (which needs further modifying to improve repeatability). It is suggested to explore this method with industry experts to observe how feasible and useful it is in practice.

Each selection strategy has limitations, but combining them strengthens the solution space. The strength of the CATSS method is that it provides a structured approach to identify secondary use applications from different perspectives. All three strategies can be applied to each sectioning level. In doing so, we expect to spark interest in repurposed blade sections and promoting structural reuse as an EoL strategy.

A thorough exploration of CATSS with thermoplastic blades as a case study is in progress, which will expand on the strengths and limitations of the process. This exploration will provide a better understanding of the material characteristics for each sectioning level. With this information, it is also expected that improvements to the original blade design will be identified. This further promotes structural reuse of blades with a broader solution space by informing design decisions. As such, the CATSS method presented can help identify new applications for thermoplastic composite products at their end-of-life, while, on the other hand, they indicate which aspects need to be considered in the original design, thus contributing to more circular practices in the composites industry.

6. Conclusion

A new methodology was proposed to identify relevant secondary applications for wind turbine blades. The Circular Applications Through Selection Strategies (CATSS) method is a systematic approach to identify applications that maximize material integrity at three different sectioning levels of wind turbine blades. The sectioning levels (segments, elements, and units) provide a path toward extending material functionality of WTBs before recycling. Since the unit level disassembles the blades' structural components into laminates, thermoplastic blades can then be reshaped, which opens up the possibilities for market sectors that have yet to be explored. The CATSS methodology was illustrated with examples found in literature that could be reframed as products of Landru strategies. This showed the approach to be promising for further exploration.

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