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Visual Similarity to Aid Alternative-Use Concept Generation for Retired Wind-Turbine Blades

The challenge of finding alternative uses for retired wind-turbine blades, which have limited disposal options, motivates this work. Two reuse concept-generation activities (CGAs) conducted in German universities revealed difficulties with the parts' large scale and seeing beyond their original use. Existing methods, e.g., using functional analogy, are less applicable, since for safety reasons, these parts should not be reused to fulfill the same function. Therefore, this work explores the use of visual similarity to support reuse-concept generation. A method was developed that (1) finds visually similar images (VSIs) for wind-turbine-blade photos and (2) derives potential-reuse concepts based on objects that are visually similar to wind-turbine blades in these images. Comparing reuse concepts generated from the two methods, VSI produced fewer smaller-than-scale concepts than CGA. While other qualities such as feasibility depend on the specific photo selected, this work provides a new framework to exploit visual similarity to find alternative uses. As demonstrated for wind-turbine blades, this method aids in generating alternative-use concepts, especially for large-scale objects. [DOI: 10.1115/1.4042336]

1 Introduction

A scenic landscape of rows of wind turbines can elicit a feeling of hope, as it signals growth in renewable energy and shows promise for a clean-energy future. There is, however, an unseen problem behind this beautiful scene. Currently, the fate of the unrecyclable parts of these wind turbines, once they are necessarily decommissioned, is unknown.

From a design-methodology perspective, this poses an interesting alternative-uses problem. While wind-turbine blades are optimized for their intended function, their aerodynamic geometry means that few sections are perfectly flat or cylindrical, which limits alternative uses. Wind-turbine blades are also much larger than the objects typically studied in Guilford's alternative uses test [1], further adding to the challenge.

2 Motivation

The lack of end-of-life options for retired wind-turbine blades, detailed below, motivates identifying alternative uses for them. This section also summarizes related work that motivates developing a method based on visually similar images (VSIs).

2.1 End-of-Life Options for Retired Wind-Turbine Parts. While most parts of the wind turbine are recyclable (i.e., made of steel, aluminum, or other recyclable materials), there are few end-of-life solutions available for the rotor blades [2]. These blades are made of several layers of glass fiber compound (GFC) or carbon fiber compound (CFC), bonded with thermoset resin infusion and other bonding agents [3]. This material composition resists mechanical separation and copes with high stress under extreme weather conditions but is difficult to recycle.

The average designed life span of wind turbines is 20 years, after which there are increased risks of structural failure. Researchers estimate that 1 kW of installed power corresponds to 10 kg of materials, i.e., 30,000 ton/year to be disposed of by 2028 [4]. This large amount of material with an uncertain end of life demonstrates the need for sustainable solutions, including options for reuse.

In general, disposal options include landfill, incineration, recycling, and reuse. Landfill is the easiest but no longer allowed in Europe due to the high (30%) organic carbon content of rotor blades [5]. Incineration in combined-heat-and-power plants uses the heat to create electricity, but 60% of the input is left behind as ash. While GFC can be incinerated, CFC should not be since it leads to high levels of small carbon fibers in the exhaust gas, a health hazard that could also cause explosions.

Thermoset-bonded GFC and CFC, unlike thermoplastics, cannot be melted by heat, severely reducing their recyclability. In a limited case of GFC thermal and material recycling, a process was developed and put in place since 2010 in Germany. Here, ashes from incinerated rotor blades are used as a corrective in clinker (lumps) composition in cement production, replacing the fossil fuels and silica used for this purpose [6].

With respect to repurposing, architects, motivated by the high-strength properties of rotor-blade parts as a new building material, have designed roofs or playgrounds. However, these are considered "occasional solutions" since no commercially viable solution exists yet that can fully absorb the amount of parts requiring reuse [7]. Thus, this work explores concepts to repurpose retired wind-turbine blades.

2.2 Support for Alternative-Use Concept Generation. Because decommissioned wind-turbine blades are excluded from reuse in their originally designed function, support for concept

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generation toward alternative uses is desired. Functionally based design-by-analogy has been shown to be effective in generating innovative, high-quality, and novel designs [8–10]. Physical models have also been used to increase variety and quality of ideas [11,12]. Visual analogy is another helpful cognitive strategy toward problem solving in the early stages of design, where pictorial analogies are more effective than verbal analogies in generating more novel ideas [13,14]. Table 1 summarizes related work with respect to method or task, how stimuli or problems are represented, and processes supporting concept generation.

While function-based approaches can enhance concept generation, they may be limited in finding alternative uses that are functionally unrelated, as required for wind-turbine blades. The large size of wind-turbine blades makes physical representation and manipulation of potential concepts more challenging. Since the use of functional similarities will likely lead to infeasible concepts for wind-turbine blades, a method using visual analogy is explored. Visual similarities can be applied to generate alternative-use concepts, which is explored by this work for wind-turbine blades.

2.3 Design Fixation and Functional Fixedness. The process of deriving alternative uses is susceptible to design fixation or a subconscious adherence to a limited set of ideas [15]. Also relevant is functional fixedness, a cognitive bias related to an inability to consider new uses or functions for well-known objects [16]. These limitations may be particularly relevant when finding alternative uses of retired wind-turbine blades, which are visually distinctive with a geometry optimized for a very specific function. The stipulation that many visually and functionally similar reuses are not viable increases the difficulty of this design problem. Thus, strategies to reduce design fixation that use functional analogy (e.g., see Ref. [17]) are less applicable to this alternative-uses problem.

Pictorial examples, however, can promote fixation in open-ended tasks, where no one correct solution exists. Jansson and Smith found that pictorial examples led engineering design students to conform to examples provided [15].

Thus, our work also aims to develop a method using visual similarity that overcomes, rather than encourages, design fixation.

3 Methods

This work compares two ways to identify alternative uses for wind-turbine blades: (1) human-generated concepts and (2) extracting concepts from images that are visually similar to photos of wind-turbine blades, as detected by image recognition. The difficulty observed in human-concept generation for this design problem, across two groups of participants, motivated the development of our method using visually similar images.

3.1 Research Questions. These techniques are compared to answer the following research questions:

- How effective is, and what are the limitations of, human concept generation of alternative uses for wind-turbine blades?
- Can alternative-use concept generation be automated, e.g., by using visual similarity?
- How effective is, and what are the limitations of, the newly developed method for alternative-use concept generation?

3.2 Concept-Generation Activity. Two iterations of a concept-generation activity (CGA) were conducted on paper with no imposed time restrictions. The instructions for each study are provided in Appendix A.

Table 1 Summary of related work supporting concept generation

	Method/task	Representation of problem/ stimulus	Process supporting concept generation
Function-based design-by-analogy	Product database search using similarity metric [8]	Functional model of design problem based on customer needs and weighted importance of functions	From set of products with highest functional similarity to customer-need functions, find possible solutions to design problem
	WordTree method to re-represent design problems with analogous domains [9]	Written problem statement and related functions	Derive key problem descriptors (action verbs), brainstorm linguistic representations, and use WordNet database to find analogies
	Find related patents by analogous functions [10]		Patent search method related to design problem by function
Physical models	Design object to bind paper together using steel wire [11]	Given steel wire pieces and tools to prototype and test ideas	Idea generation supported by sketching and/or building and/or testing prototypes, with building resulting in higher quality and functionality
	Produce innovative concepts for an object shown pictorially or physically [12]	Pictorial or physical representation of object to innovate upon	Physical model visually inspected or dissected, with dissection leading to higher variety
Visual analogy	Architectural design problem [13]	Visual displays of ~12 pictures, representing potential analogies of design problem	Solve design problem with or without explicit requirement to use visual analogy, with use aiding in successful completion of problem
	Analogy seeded mind-map [14]	Mind-map to graphically represent a key function with related verbal versus pictorial analogies	Idea generation based on words or pictures related to a functional design requirement, with pictorial analogies producing more novel ideas

Table 2 Concept-generation activity participant data

CGA iteration	Number of participants	Participant gender: [scale gender]	Age distribution	Difference in instructions between CGA iterations
1 (Oldenburg)	28	11F: [4F, 7M] 17M: [10F, 7M]	22–25: 11 26–29: 10 30+: 7	• No restrictions on reuse • Human scale shown next to wind-turbine parts
2 (Bremen)	26	7F: [4F, 3M], 19M: [10F, 9M]	22–25: 12 26–29: 12 30+: 2	• No wind-turbine, airplane, or similar applications • Enlarged human scale on cover page

3.2.1 Participants and Procedure. Participants were graduate students in two courses at German universities in Fall 2016. In the first concept-generation activity (CGA-1), students in a course on Biomass Energy at Oldenburg University were invited to participate in the study for the latter part of a regularly scheduled lecture. In a subsequent concept-generation activity (CGA-2), masters-level students in a course on "Engineering Design: Methods and Tools" at Bremen University also participated in the study. Due to the many international students in the first course, English was the language of instruction as well as of the study. While the second study was also conducted in English, students were able to ask for definitions or translations for unknown words in English and could describe their concepts partly or wholly in German.

Participants were asked to identify their field of study, the last year of study completed, their gender, and their age. Table 2 summarizes participant (and scale) gender, age, and differences in instructions. Oldenburg (CGA-1) participants were 28 graduate students mostly in Renewable Energy and Engineering Physics. Bremen (CGA-2) participants were 26 students mostly in Industrial, Production, and Systems Engineering Programs.

3.2.2 Use of Images and Scale. Images of four wind-turbine-blade parts were shown to participants on separate pages, each represented by three orthogonal views and at least one isometric view; if the part is hollow, another isometric view showed the part cut to reveal the inside. The four parts were consistently shown in the same order. Figure 1 shows all views for part 1. Figure 2 shows all parts represented by the isometric view with a human scale.

Pilot studies revealed that the images must be accompanied with a scale to convey part size. While a human comprises a highly intuitive scale, it was unclear whether the scale's gender would affect concept generation, so an equal number of each was used. However, CGA-1 participants noted after the study that the human scale next to the wind-turbine part was too small to differentiate gender. Thus, a much larger version of the same scale was provided on the first page of the worksheet to "clarify" the use of the scale for CGA-2.

3.2.3 Participant Instructions. Participants at both universities were instructed to identify how to reuse each of the parts shown, maximizing the reuse of each part and cutting if necessary (though minimally, as needed). No requirements on the minimum or maximum number of reuses were specified. Participants were also provided information about the parts' material (i.e., fiber-reinforced composites with high strength/stiffness and low density). CGA-1 participants were not informed of the original use of the parts as wind-turbine blades. This was done to reduce the likelihood of functional fixedness on the original use, as these parts cannot be reused as wind-turbine blades. However, since over a third of CGA-1 concepts were for use in wind-turbine, airplane, or similar applications, CGA-2 participants were explicitly told to exclude these. For CGA-2, a larger version of the human scale shown in Figs. 1 and 2 was shown on the worksheets' cover page in the context of explaining its use as a scale. The enlarged scale was actually intended to clarify the scale's gender, which CGA-1 participants said they could not differentiate. Both sets of instructions are included in Appendix A. The results of these changes in instruction are discussed below.

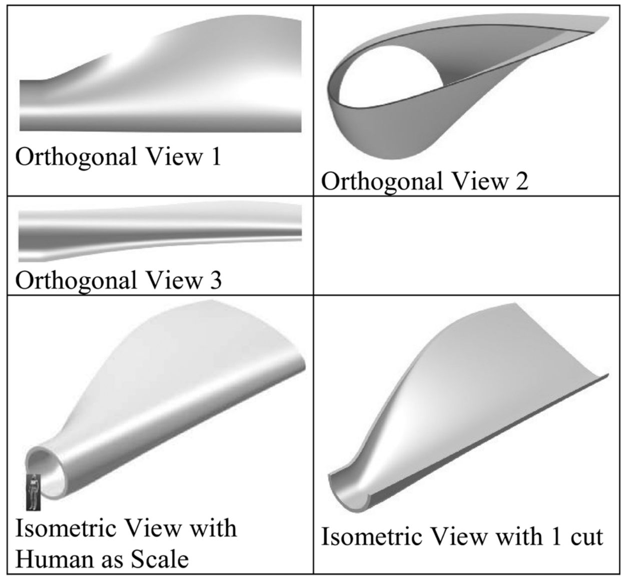

Fig. 1 Computer-aided design images for part 1 with the female scale

3.3 Computer-Generated Visually Similar Images.

Images that are visually similar to photos of decommissioned or not-yet commissioned wind-turbine blades were also considered as potential sources of alternative-use concepts. Computer-generated visually similar images were used to directly derive alternative-use concepts and not as stimuli for human concept generation. Photos

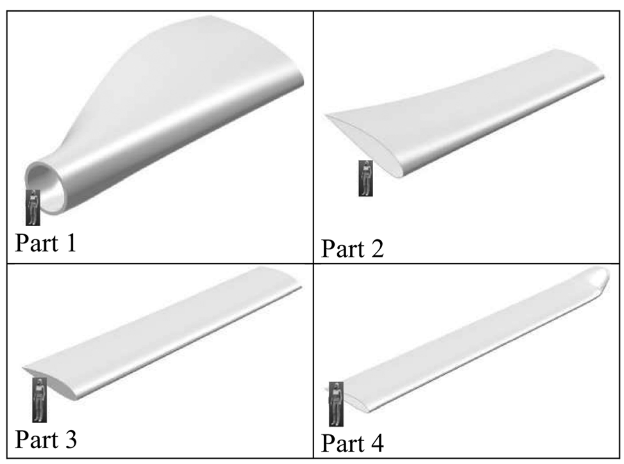

Fig. 2 Isometric views of wind-turbine-blade CAD images for parts 1–4 with female scales

were chosen over computer-aided design (CAD) images so that images obtained by VSI were not other CAD images or stock photos that often feature gray-scale images of products on white backgrounds. Using photos of wind-turbine blades specifically enables comparison with the CGA problem. These photos were used as input for Microsoft Azure's Bing Image Search application program interface (API) [18], which returned up to a maximum of 100 website addresses for image files that are visually similar to the original wind-turbine blade photo. Objects in the visually similar photos that correspond to the wind-turbine blade in the original photo were identified as potential reuses for wind-turbine blades, as detailed below.

3.3.1 Source Photo Selection. The photos of wind-turbine blades shown in Fig. 3 were chosen as source photos from which to obtain visually similar images. These photos were selected to explore the effect of different features in the image, e.g., one versus multiple wind-turbine blade(s) and different background features. Photo A (Fig. 3(*a*)) contextualizes a single wind-turbine blade with grass, trees, and sky. Photo B (Fig. 3(*b*)) displays multiple wind-turbine blades with gravel, buildings, and sky. Photo C (Fig. 3(*c*)) displays a transported wind-turbine blade on the road. These specific photos were chosen over others with similar features because they had at least 100 visually similar images, which upon a quick visual inspection displayed a diversity of images.

3.3.2 Identifying Visually Similar-Image Features. Some visually similar images contained features that were difficult to identify by human raters from the photo alone. In these instances, Google's "Search by image" function was used to access the online source of the photo to help identify its content. The advantage of using a web-based image-recognition tool such as Bing's Search API is this ability to identify the origin of visually similar images. The use of the object featured in one example VSI result for photo A was initially unclear; searching for the image's source revealed that it is called a "fuwa-fuwa" dome, a Japanese play structure, whose use is clarified in Fig. 4.

4 Evaluation Procedure

Concepts from both human-generated and (computer-generated) visually similar sources were evaluated on (1) whether a potential reuse could be identified, (2) whether the concept was a prohibited reuse, (3) the scale of the reuse concept in relation to

(*a*)

(*b*)

(*c*)

Fig. 3 (*a*) Photo A: single wind-turbine blade, (*b*) photo B: multiple wind-turbine blades, and (*c*) photo C: transported wind-turbine blade

Fig. 4 "Fuwa-fuwa dome" shown in use after searching by image to identify the content of the VSI result of photo A (Photo credit by nekoneko and licensed for reuse under creativecommons.org/licenses/by-sa/3.0)

the wind-turbine blade, and (4) the feasibility of the reuse. This section describes how concepts were identified and interpreted, and how human raters assessed these measures.

4.1 Interpretation of Concept-Generation Activity Concepts. Concept-generation activity participants provided written responses, sometimes alongside sketches, drawn next to or over the provided images, and/or a reference to the specific view of the part reused.

Participants' sketches were used to verify the particular part reused and the way in which it was reused. For example, the response "children's amusement thing" was interpreted as "a slide" by the sketch provided, shown in Fig. 5 (right). The sketch also suggests that the isometric view with one cut of part 1, the first section of the blade, was used in the orientation shown.

If no sketch was provided, but the sectional view being used was specified, the nature of the reuse could generally be easily interpreted. When the reuse was unclear, a Google Images search of the written concept aided in interpreting the concept.

For example, a participant wrote "tip of syringe" in response to orthogonal view 3 of part 1, as shown in Fig. 6. Searching for the quoted text on Google Images led to pictures of syringe tips and caps that are visually similar to the part, leading to the conclusion that the participant rescaled the part by shrinking.

When concepts were described with words only (i.e., with neither sketches nor reference to the view used), the intended reuse was inferred. For example, on the worksheet page for part 1, a participant wrote "Used for cutting." This was interpreted as using orthogonal view 1 of part 1, shown in Fig. 1, as a knife blade. This use also likely involved shrinking the part.

Each concept listed by the participant was considered separately, including those where "same as above" was stated (i.e., duplicate responses) and was counted twice. Blank or nondescript responses, e.g., "orthogonal view 1 possesses high strength," were categorized as unidentifiable reuse concepts.

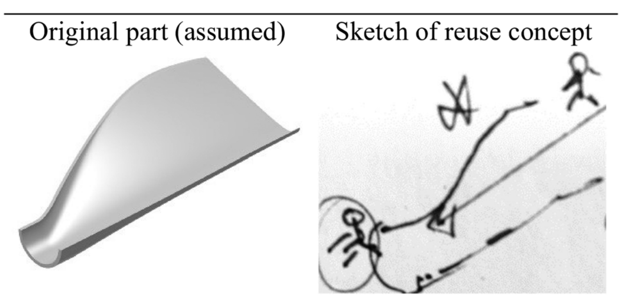

Fig. 5 Slide concept (example response w/sketch)

Fig. 6 Syringe tip cap, example of inferred visual association (Photo credit by Fifo and licensed for reuse under creativecommons.org/licenses/by-sa/2.5)

4.2 Interpretation of Visually Similar Image Concepts. Potential-reuse concepts were extracted from the VSIs as follows. The search API detected images that were visually similar to the original wind-turbine-blade photo. The content of these API-detected images was then interpreted and compared to the original photo of the wind-turbine blade. For example, in photo A (Fig. 3(*a*)), the wind-turbine blade is visually distinct from the grass, trees, poles, and sky. Each VSI also contains a component that is most visually distinct from the background. This component was identified and analyzed as a potential-reuse concept by human raters. For example, the VSI in Fig. 7 includes grass, trees, poles, and sky, as did photo A (Fig. 3(*a*)). Different from photo A, the skate park is visually distinct from these other shared features and identified as the potential-reuse concept. This process is summarized in Fig. 8.

A single potential-reuse concept was identified from each VSI, based on the feature most distinct from the background (or most similar to the wind-turbine blade). Images missing components visually similar to the wind-turbine blade were categorized as having unidentifiable reuse concepts. Unidentifiable reuses were excluded from further evaluation. Abstract or nonsolid features, e.g., visually similar component representing fog or mist, would also be considered unidentifiable reuses. While identification of the potential-reuse concept was straightforward, the few disagreements between two independent raters on the most visually similar component of the image to the wind-turbine blade were discussed and reconciled.

4.2.1 Prohibited Reuses. First, each concept was checked against the following list of concepts, which are prohibited for safety reasons:

– Wind-turbine/mill part/blade
– Rotor blade
– Airfoil (unless specified for wind-tunnel studies)
– Airplane part/whole
– Propeller

Next, scale and feasibility were measured for responses with identifiable reuses that were not prohibited.

4.2.2 Scale Compared to Wind-Turbine Blade. The scale of the reuse concept in relation to the wind-turbine blade was classified as either shrunk, to-scale, or enlarged. Shrunk refers to

Fig. 7 Example of VSI for the wind-turbine-blade photo (Photo credit by Gary Rogers and licensed for reuse under creativecommons.org/licenses/by-sa-2.0)

when the part had to be reduced in scale to enable the stated reuse, e.g., "ski," corresponding to part 4 of the wind-turbine blade (Fig. 2). To-scale refers to when the correct scale of the part was apparent from the reuse, including when parts were cut or combined. A to-scale reuse of a minimally cut part is a slide, previously described for part 1. In contrast, a to-scale reuse that requires significant cutting includes making floor tiles. Finally, a to-scale reuse that involves combining is to use multiple parts for walls. The amount of cutting or combining required is accounted for when assessing feasibility of the reuse, described below. Enlarged refers to when the scale of the reuse was larger than the part, an example of which is a whole building, without reference to combining multiple parts.

Participant descriptions (written and/or sketched) including required cuts were used to differentiate smaller-than-scale reuses that require cutting (to-scale) versus shrinking (shrunk). Participant descriptions also gave insight into when the scale of the part was understood correctly, but the concept was abstracted from a smaller-than-scale reuse. An example of this is "giant ski," derived from a normal ski resembling wind-turbine-blade part 4. Such concepts were categorized as to-scale but infeasible.

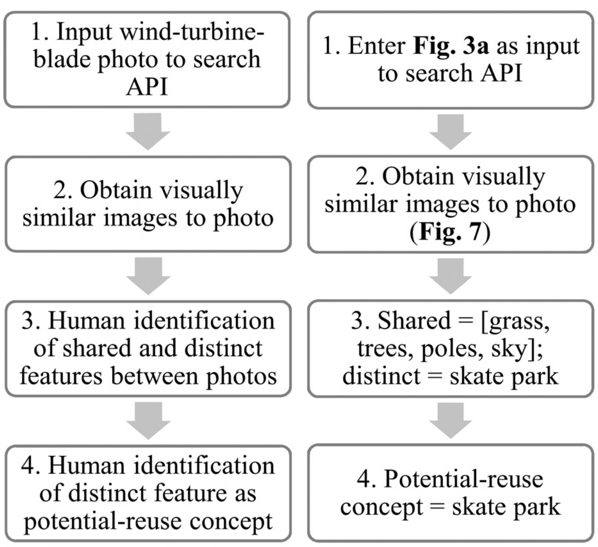

Fig. 8 (Left) process of identifying reuses from VSIs, using example (right)

Plurality in responses, e.g., "many pieces," was used as a cue for multiple parts used and therefore categorized as to-scale.

4.2.3 Feasibility of Reuse. Potential-reuse concepts were categorized as infeasible, or of low, moderate, or high feasibility, to account for technical requirements, structural specificity, and level of modification from the provided wind-turbine-blade part. Infeasible reuses include shrunk and to-scale concepts abstracted from a smaller-than-scale reuse, as described above. A low-feasibility-reuse example is a space rocket, where high technical requirements are unlikely met by wind-turbine blades pre-emptively retired due to concerns over structural integrity. In contrast, a highly feasible possible reuse is a fence due to low technical requirements and modification from the original part. A moderately feasible reuse is a storage shed, which does not have high technical demands, but would require more modification of the wind-turbine blade, e.g., arrangement of multiple cut pieces. Since these reuse ideas are at an early conceptual stage, an estimated assessment of feasibility is used as a measure of quality [19].

Since evaluating feasibility introduces bias, Cohen's Kappa, used to determine inter-rater reliability between two independent raters, was found to be >0.81, or almost perfect [20]. Differences in ratings were discussed between raters and reconciled accordingly prior to analysis.

5 Results

For the analysis, reuse concepts from the following methods are compared: two iterations of the CGA and VSI for three photos (Fig. 3). For the two iterations of CGA, concepts are combined across the four wind-turbine parts shown to participants. As mentioned, repeated responses from a single participant were separately counted. To ensure that this did not render CGA responses overly redundant, CGA concepts with and without participants' duplicates were compared. Chi-square tests comparing frequency counts for each measure with duplicate responses included and removed reveal no significant differences in CGA-1 or CGA-2. Whether duplicates were included or removed did not significantly affect the proportion of unidentifiable or prohibited results expected or the distribution of reuses of different scales and feasibilities. The frequencies of duplicates in CGA concepts, and their effect on each measure, are shown in Appendix B (Table 8).

Results from Oldenburg (CGA-1) and Bremen (CGA-2) are compared to reveal effects of the different instructions provided to participants. The VSI results for the three photos (photos A–C)

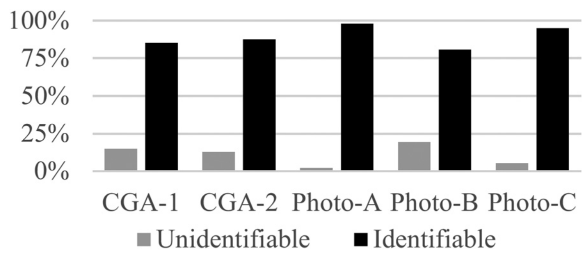

Fig. 9 Unidentifiable versus identifiable reuses

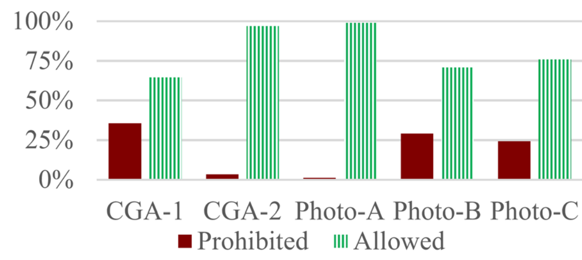

Fig. 10 Prohibited versus allowed reuses

are compared to examine the effect of different features of these photos, e.g., background, single versus multiple blades. These comparisons aim to clarify the value and limitations of using VSI to aid in generating reuse concepts.

5.1 Comparison of Unidentifiable Reuses. Since unidentifiable concepts are undesirable, it is useful to predict the tendency of each method to produce them, which can be done using a binary logistic regression model. That is, each method can be compared to CGA-1 to see if CGA-2 and VSI results are more/less likely to produce unidentifiable results. Figure 9 shows the proportion of unidentifiable versus identifiable reuse concepts for each method, as summarized in Table 3.

CGA-1 was not associated with significantly higher odds of producing unidentifiable results than CGA-2 (odds ratio: 1.2 times (95% CI: [0.62, 2.3])), which is expected since no intervention was added in CGA-2 to reduce the frequency of unidentifiable responses. Compared to photo A, CGA-1 is 8.3 times (95% CI: [1.9, 36.1]) more likely to produce unidentifiable results. Compared to photo C, CGA-1 is 3.2 times (95% CI: [1.2, 8.6]) more likely to produce unidentifiable results. No significant improvements on CGA-1 were made by photo B. CGA-2 is also more likely to produce unidentifiable results than photo A by 7.0 times (95% CI: [1.6, 30.8]), but no such improvements are made by photos B or C. These differences are discussed below.

5.2 Comparison of Prohibited Reuses. Prohibited reuses are also undesirable concepts, and the likelihood of each method to produce them is compared using a binary logistic regression model. The proportion of prohibited versus allowed reuses for each method is shown in Fig. 10, and frequencies are summarized in Table 4. Compared to photo A, CGA-1 is 52.3 times (95% CI: [7.1, 386.8]) more likely to produce prohibited reuses. However, the opposite effect is shown between photo B and CGA-2 (i.e., photo B is more likely to produce prohibited reuses than CGA-2 by 12.3 times (95% CI: [4.1, 37.0])). Similarly, photo C is 9.5 times (95% CI: [3.2, 28.6]) more likely than CGA-2 to produce prohibited reuses. Reasons for these differences between photos are discussed below.

5.3 Comparison of the Reuse Scale. A multinomial regression is used to model the expected scale of reuses and compare the odds of CGA versus VSI to produce not-to-scale reuses. Ideally, reuses incorporate the correct scale, including those that cut or combine the parts of the wind-turbine blade. The model therefore predicts the tendency of CGA versus VSI to produce reuses that deviate from the correct scale. Table 5 and Fig. 11 compare reuse scales: to-scale, shrunk, and enlarged.

Consistent with the observed tendency for CGA participants to shrink the shown parts for reuse, CGA was 5.8 times (95% CI: [2.0, 17.1]) more likely than VSI to produce shrunk than to-scale reuses. Conversely, VSI is 20.0 times (95% CI: [4.8, 83.3]) more likely than CGA to produce enlarged than to-scale reuses. Enlarged VSI reuses result when the visually similar object is larger in scale than the wind-turbine blade in the original photo. Implications of these findings are discussed below.

5.4 Comparison of Reuse Feasibility. An ordered multinomial regression is used to predict the expected level of reuse feasibility (i.e., the likelihood of producing decreasingly feasible reuses) and compares the methods using odds ratios. Figure 12 shows the comparison of reuse scales, and Table 6 shows corresponding frequencies.

Table 3 Frequency of unidentifiable versus identifiable reuses

Method	Count	Unidentifiable	Identifiable	Total
CGA-1	Count	24	138	162
	% within method	14.8	85.2	
CGA-2	Count	18	124	142
	% within method	12.7	87.3	
Photo A	Count	2	96	98
	% within method	2.0	98.0	
Photo B	Count	19	79	98
	% within method	19.4	80.6	
Photo C	Count	5	91	96
	% within method	5.2	94.8	
Total	Count	68	528	596

Table 4 Frequency of prohibited versus allowed reuses

Method	Count	Prohibited	Allowed	Total
CGA-1	Count	49	89	138
	% within method	35.5	64.5	
CGA-2	Count	4	120	124
	% within method	3.2	96.8	
Photo A	Count	1	95	96
	% within method	1.0	99.0	
Photo B	Count	23	56	79
	% within method	29.1	70.9	
Photo C	Count	22	69	91
	% within method	24.2	75.8	
Total	Count	99	429	528

Table 5 Frequency of the reuse scale

		Scale of reuses			
Method	Count	Shrunk	To-scale	Enlarged	Total
CGA-1	Count	15	73	1	89
	% within method	16.9	82.0	1.1	
CGA-2	Count	9	110	1	120
	% within method	7.5	91.7	0.8	
Photo A	Count	0	74	21	95
	% within method	0	77.9	22.1	
Photo B	Count	4	50	2	56
	% within method	7.1	89.3	3.6	
Photo C	Count	0	53	16	69
	% within method	0	76.8	23.2	
Total	Count	28	360	41	429

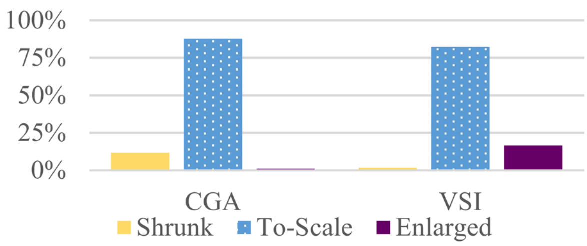

Fig. 11 Comparison of the reuse scale

Table 6 Frequency of reuse feasibility

Method	Count	Feasibility of reuses: Infeasible	Low	Moderate	High	Total
CGA-1	Count	15	9	17	48	89
	% within method	16.9	10.1	19.1	53.9	
CGA-2	Count	20	16	39	45	120
	% within method	16.7	13.3	32.5	37.5	
Photo A	Count	0	19	37	39	95
	% within method	0	20.0	38.9	41.1	
Photo B	Count	4	10	21	21	56
	% within method	7.1	17.9	37.5	37.5	
Photo C	Count	0	36	28	5	69
	% within method	0	52.2	40.6	7.2	
Total	Count	39	90	142	158	429

CGA-1 and CGA-2 did not differ significantly in likelihood of producing lower-feasibility reuses. Since additional instructions in CGA-2 targeted prohibited reuses, allowed reuses are not expected to be more or less feasible.

Reflecting photo C's few highly feasible reuses and many low-feasibility reuses, the only significant differences in expected feasibility between CGA and VSI were between photo C and both CGA iterations. Photo-C had 3.7 (95% CI: [2.1, 6.6]) times and 2.2 (95% CI: [1.3, 3.6]) times increased odds of producing low-feasibility reuses than CGA-1 and CGA-2, respectively. Reasons for implications of photo C's low-feasibility results are discussed below.

5.5 Differences Between Photos. Rather than performing pairwise comparisons between photos used for VSI for each measure, chi-square tests were used to identify and analyze differences between photos. Table 7 compares the number and percentage of reuse concepts between sets of VSI across each measure. Chi-square tests revealed significant differences between photos in the frequency of each measure's levels. According to chi-square test assumptions, levels with expected values of <5 are excluded from comparison [21].

Regarding the difference in proportion of unidentifiable versus identifiable reuses between photos, $\chi^2\ (2, 292) = 20.6$, $p < 0.0001$. As shown in Table 7, photo A is associated with fewer than expected unidentifiable reuse concepts (2.0% versus 8.9%), photo B is associated with more (19.4% versus 8.9%), and photo C did not differ significantly from expected.

Table 7 next compares photos by the percentage of prohibited and allowed reuses. Assuming no differences between photos, the expected frequency of prohibited reuses is 17.3%. There is a difference between photos, $\chi^2\ (2, 266) = 28.5$, $p < 0.0001$: photo A is associated with a low frequency of prohibited reuses (1.0%), and photo B (29.1%) and photo C (24.2%) with a high frequency.

Table 7 also compares the scale of reuse concepts between photos. Due to the low number of shrunk concepts across all three photos (<5), photos are compared with respect to frequency of to-scale and enlarged concepts. A significant difference in scale between photos was found, $\chi^2\ (2, 216) = 9.4$, $p < 0.01$. The expected association with enlarged concepts is 17.7%: photo A (22.1%) and photo C (23.2%) associated more strongly with

Table 7 Comparison between VSI photos

Measure	Level	Count	Photo A	Photo B	Photo C	Total[a]
Unidentifiable reuses	Unidentifiable	Count	2	19	5	26
		% within photo	2.0	19.4	5.2	8.9
	Identifiable	Count	96	79	91	266
		% within photo	98.0	80.6	94.8	91.1
	Total	Count	98	98	96	292
Prohibited reuses	Prohibited	Count	1	23	22	46
		% within photo	1.0	29.1	24.2	17.3
	Allowed	Count	95	56	69	220
		% within photo	99.0	70.9	75.8	82.7
	Total	Count	96	79	91	266
Scale	Shrunk	Count	0	4	0	4
		% within photo	0	7.1	0	1.3
	To-scale	Count	74	50	53	177
		% within photo	77.9	89.3	76.8	80.5
	Enlarged	Count	21	2	16	39
		% within photo	22.1	3.6	23.2	17.7
	Total	Count	95	56	69	220
Feasibility	Infeasible	Count	0	4	0	4
		% within photo	0	7.1	0	1.8
	Low	Count	19	10	36	65
		% within photo	20.0	17.9	52.2	29.5
	Moderate	Count	37	21	28	86
		% within photo	39.0	37.5	40.6	39.1
	High	Count	39	21	5	65
		% within photo	41.0	37.5	7.2	29.5
	Total	Count	95	56	69	220

[a]Total percentages for each level represent expected frequencies if no difference in number of each measure between photos.

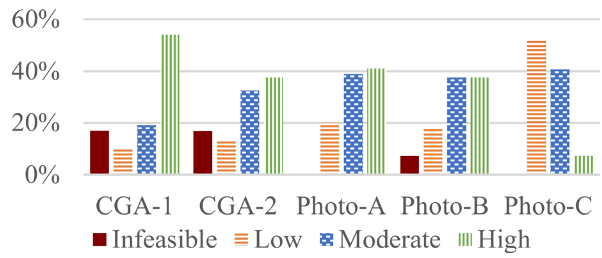

Fig. 12 Comparison of reuse feasibility

enlarged concepts. In contrast, photo B (3.6%) associated more weakly than expected with enlarged concepts; its multiple wind-turbine blades imply a larger scale that is difficult to further enlarge.

Finally, Table 7 shows that the use of different photos also affects the feasibility of reuse concepts, χ^2 (4, 216) = 34.1, $p < 0.0001$. Since the overall frequency of infeasible concepts is <5, only frequencies of low, moderate, and high feasibility are considered. The expected association with highly feasible concepts is 29.5%. Photo C has lower than expected high-feasibility reuses (7.2%); 52.2% of photo C concepts have low feasibility. Reasons for these differences are postulated below.

These comparisons confirm that the source photos are independent and that effectiveness of the image in avoiding undesirable concepts depends on the photo used.

5.6 Differences in Concept-Generation Activity Iterations. As stated earlier, two major changes were made in CGA-2 from CGA-1. The resulting effects of these changes, and their possible causes, are now discussed.

Using a binary regression model to predict the tendency to produce prohibited reuses, the odds of CGA-1 producing prohibited reuses are 16.5 times (95% CI: [5.7, 47.5]) higher than CGA-2. This can be expected, since CGA-2 participants were explicitly told to exclude these reuses.

With respect to scale, a chi-square test revealed a significant difference in the frequency of shrunk reuses in CGA-1 and CGA-2, χ^2 (1, 207) = 4.4, $p < 0.05$. CGA-1 reuses are 2.3 times (95% CI: [1.0, 4.9]) more likely to be shrunk versus to-scale than CGA-2. A better perception of the correct scale may be the result of CGA-2 participants being told what they were shown images of, with an emphasized human figure for scale.

While the two activities were not framed or motivated any differently, the backgrounds of the two groups of students may have affected the number and types of concepts they provided. CGA-2 participants were from an engineering-design-related course and produced more categories of concepts (28 versus 18) than the CGA-1 participants from an energy-related course. CGA-2 participants produced 16 categories of alternative uses (e.g., related to civil works, transportation, and public infrastructure) that did not overlap with CGA-1, whereas only five CGA-1 categories were not found in CGA-2.

The design-related nature of the course taken by CGA-2 participants, along with other differences noted above, may explain differences in variety of concepts.

5.6.1 Gender of Figure Used for Scale. To examine the effect of receiving instructions with either a male or female figure for scale, chi-square tests were performed. For each measure, the effect of the gender of the human figure was significant, but the scale's gender differently affected whether the reuses were undesirable.

Combining participants across the two CGA iterations, the figure's gender significantly affects whether concepts were unidentifiable, χ^2 (1, 304) = 5.4, $p < 0.05$. The odds of producing unidentifiable versus identifiable reuses were 2.0 times (95% CI: [1.1, 4.4]) higher when shown a male versus female figure. Also affected is the frequency of prohibited reuses, χ^2 (1, 262) = 4.8, $p < 0.05$, where the presence of a female scale had 2.0 times higher odds of producing prohibited reuses. Comparing shrunk versus to-scale reuses, the difference between male and female figures, χ^2 (1, 207) = 4.4, $p < 0.05$, is seen in the 2.6 times (95% CI: [1.0, 6.6]) higher odds of the male figure resulting in shrunk reuses. Finally, feasibility of reuse is dependent on the figure's gender, χ^2 (3, 209) = 8.8, $p < 0.05$, with the female scale associated with a higher than expected (18.5% versus 12.0%) proportion of low-feasibility reuses.

To further investigate these effects, male versus female and CGA-1 versus CGA-2 participants receiving the same gendered figures were compared. Whether the gender of the participant and scale matched and whether the scale was enlarged did not seem to affect the effect of the figure's gender. No recommendations on the gender of human figures used for scale can be made based on these results.

6 Discussion

Compared to CGA-1, some photos led to VSI concepts with fewer unwanted reuses (i.e., those that are unidentifiable, prohibited, shrunk, or infeasible). The significant differences between the three photos demonstrate that the improvement over CGA results by VSI is highly dependent on the specific photo. The possible causes and effects of these differences are as follows.

6.1 Visual Context or Background of Photos. An important component of VSI may be the context or background in the selected photos of wind-turbine blades. This context is generally unavailable in CAD representations of wind-turbine blades. For the three photos studied, visual context was key to producing results that are significantly different between photos and from human-generated concepts. Using three photos of wind-turbine blades that were contextualized by different features led to a diverse set of visually similar images.

The possible relevance of context-specific differences between photos is demonstrated by the types of concepts derived from each photo, as summarized in Appendix C (Tables 9 and 10). VSI of photos A and B produced water-related reuses such as dams or embankments. These were missing from VSI of photo C, which prominently featured a road, and were therefore associated with transportation-related reuses such as tanker trucks and trailers. Whether these differences are specifically attributable to the features of each photo requires further analysis of different photos with similar features.

6.1.1 Visual Distinctness and Unidentifiable Uses. Photos A and C's low frequency of unidentifiable concepts compared to photo B's high frequency may be explained by the photos' backgrounds. In photo A, while the white wind-turbine blade is visually distinct from the blue-sky and green-grass background. In photo B, there is less visual distinction between the wind-turbine blades and the overcast-sky and gravel background. If the wind-turbine blade were not prominently visible in the photo used, more visually similar images with unidentifiable reuses would be expected. To test this hypothesis, photo B's color was enhanced (by increasing tint/lightness and warmth) to increase the wind-turbine blade's visual distinction from the photo's background. This enhancement led to fewer instances (6% versus 19%) of unidentifiable concepts, as fewer objects visually similar to the turbine blade represented bodies of water.

6.1.2 Unlikely Setting and Prohibited Uses. The background of the pictured wind-turbine blade may also explain differences between photos in the number of prohibited reuses generated. Photo A shows a wind-turbine blade in a more unlikely position (i.e., lying on grass), possibly explaining the fewer resulting prohibited reuses. Visually similar images of photo B, however, consist of many photos (23) containing wind turbines or planes. This may be because photos of airplane wings or whole airplanes are commonly taken with backgrounds similar to photo B, i.e., sky and asphalt. Photo C, which prominently features a road, is visually similar to many photos (22) of wind-turbine parts being transported by trucks. Both photo B and photo C led to more prohibited reuses.

6.1.3 Contextual Features and Scale. The photos' contextual features may have imparted the wind-turbine blade's scale more effectively than the human figure used in CGA. In particular, no concepts from photos A or C were shrunk. Potential future work is to test whether these contextual features, e.g., trees or cars, present in photos could lead to fixation if presented to people for concept generation. While photos used as examples for idea generation tasks have not shown differences in fixation compared to sketches [22,23], the effect of multiple unrelated features in an alternative-uses test is unclear. We have shown that image recognition can help detect interesting possible alternative-use concepts at the correct scale without a significant reduction in unique categories of reuse.

6.1.4 Contextual Features and Feasibility. Differences in feasibility were also observed between photos. Photo-C is associated with fewer highly feasible reuses since the road in the photo led to many tanker-truck VSI concepts. Tanker trucks are less feasible than, e.g., fences that more commonly resulted from photos A and B. The reuses found depend on the visual context of the photo used, which, in turn, may affect the feasibility of resulting potential-reuse concepts.

6.2 Shrunk and Enlarged Concepts From Concept-Generation Activity Versus Visually Similar Images. Concept-generation activity participants identified reuses that required shrinking the shown part, whereas no such concepts arose from VSI of photos A and C. Although some CGA reuse concepts were smaller than the wind-turbine blade, they were based on cutting the true part into smaller pieces. This indicated higher feasibility and awareness of the reuse scale relative to the part. Although feasible, concepts requiring that the part be cut and used in small pieces are less interesting as this cutting can require significant effort and resources. However, despite the human-figure scale, some CGA participants identified shrunk reuses based on visual similarity to the part, e.g., "could be a ski." Naming this as a reuse ignores the true scale, and unfeasibly shrinks the part.

Other researchers found that novice designers had difficulty visualizing components of a design activity in two dimensions, preferring to visualize a three-dimensional or physical model; in contrast, experienced designers possibly overcame this by referring to past designs [24]. The tendency by our CGA participants to shrink the shown parts may be due to lack of experience designing at this scale.

For building design, researchers have developed a tool relating sketches to images of flowers, furniture arrangements, or other buildings, to support the way architects employ visual analogy to objects at different scales with similar shapes [25]. Such a tool may also help develop the experience of using visual similarity at different scales without compromising feasibility. For photos A and C, the use of visual analogy by image recognition reduced this misinterpretation of scale and source of infeasible reuses.

While CGA participants tended to shrink or cut up the parts shown, many visually similar images of photo A contained features that are much larger than the wind-turbine blade, e.g., on the scale of large buildings. To avoid this "enlargement" effect, more size-specific features, such as cars or people, can be used to impose scale. A landscape, like the one shown in photo A, can be too ambiguous at a larger scale.

However, enlargement in reuses from visually similar images may not be as problematic as shrinking in human-generated concepts. While all shrunk reuses (without further abstraction, see below) are infeasible, enlarged reuses are not necessarily infeasible. No enlarged reuses in this work were considered infeasible, since, for example, a large wall or simple structure could be achieved by a combination or arrangement of multiple wind-turbine-blade parts.

7 Qualitative Description of Observations

Some interesting and surprising results from both participant responses and visually similar images are qualitatively discussed in this section. Implications for future work are proposed.

7.1 Concept-Generation Activity and Abstraction to Scale. The two CGA iterations differed in whether participants were not told (CGA-1) or told (CGA-2), what the parts and prohibited reuses were. In addition, CGA-2 instructions emphasized the presence of the human scale. Due to these differences, fewer prohibited and shrunk reuses were expected in CGA-2.

As expected, CGA-2 had significantly fewer shrunk and more to-scale reuses than CGA-1. However, CGA-2 participants abstracted infeasible to-scale reuses from shrunk concepts, e.g., giant bottle opener, giant jumping board, and giant blender blade. Such concepts demonstrate awareness of the wind-turbine blade's true scale but not an increase in feasible reuses. Many other CGA-2 concepts were both shrunk and infeasible. Yet other concepts cut the large ski-like blade into correct-scale skis, possibly demonstrating fixation to the concept of skis. Future work should explore how to reduce the effects of fixation in this design problem by human participants.

7.2 Visually Similar Images and Detailed, Domain-Specific Alternative Uses. Highly domain-specific concepts were found in the VSI results that were not seen in CGA results. For example, several concepts from both CGA iterations (13 in CGA-1 and 10 in CGA-2) were of flood-protection structures or other water retention, direction, or collection devices. These concepts tended not to be described in great detail regarding how they could be assembled or implemented. The scale and utility of the proposed uses were also not specified, e.g., hydroelectric dams versus smaller municipal dams. In contrast, photo B's VSI results offered fewer concepts (7) relating to river and water-resource engineering but showed different types of dams, embankments, or dikes at various scales.

Another interesting example that illustrates the difference in detail and domain specificity involves material-reuse concepts in CGA versus VSI. In CGA-2, one concept proposed, "shredding…to make packaging material." In contrast, photo C returned a picture of a specific type and brand of composite mat, which has similar properties to wind-turbine blades. Identifying uses of this specific mat may lead to other possible reuses of wind-turbine blades.

As described above, the domain specificity and detail shown in these photos can be higher than those in concepts proposed by CGA participants. Thus, VSI may offer a higher level of detail and domain specificity than CGA.

7.3 Abstraction to Improve Poor Reuses From Visually Similar Images. Although some visually similar images provide poor or not-viable reuses of wind-turbine blades, e.g., a swimming pool, these results may still be useful as stimuli for concept generation.

This can be achieved by functionally abstracting concepts from the VSI, which can serve as stimuli for reuses that may not otherwise be identified by humans. For example, a photo of a swimming pool provides two possible reuse concepts: the pool deck, which is more visually similar to the wind-turbine blade and a moderately feasible concept, and also the pool itself. Though the swimming pool may not be a directly useful concept, it could be used as a visual stimulus for an object holding water. Another example is sand on a beach, which as a direct reuse of a wind-turbine part has limited feasibility. Sand could however perform the function of protection from flooding, which is a more feasible application of the wind-turbine blade. Such abstraction could be applied to other images with nonobvious direct reuses.

7.4 Human Involvement in Concept Generation. Some examples specific to CGA reveal the unique possibilities offered by human involvement in concept generation and thus the limitations of VSI. The physical manipulation required to transform a wind-turbine blade to, e.g., floor tiles in CGA-2 is a process lacking in VSI results. Descriptions and sketches of how parts could be cut to make particular building components offer specificity unique to CGA, different from the specificity described above for VSI.

Also missing in VSI are references to specific physical features of the parts, such as the rounded end in part 1. In CGA, participants who noted this feature developed several pipe-related concepts. Further unique to CGA is the alternative use of the shown parts as mounts for solar panels. This application reflects an interest in sustainability (or fixation to renewable energy), unavailable in VSI. In summary, while VSI can provide detailed, specific, and promising reuse concepts, the value of human involvement in concept generation cannot be neglected.

8 Conclusions and Future Work

In this work, potential reuses for wind-turbine blades were (1) obtained in two concept-generation activities and (2) extracted from visually similar images of three wind-turbine-blade photos.

8.1 Research Questions Revisited. Our work addressed the first research question, "How effective is, and what are the limitations of, human concept generation of alternative uses for wind-turbine blades?" Human concept generation revealed difficulty with the large scale of the parts and fixation with what the parts looked like, e.g., a (giant) ski. These limitations inspired the development of a new method to support alternative-uses concept generation. In this method, potential reuse concepts were identified directly from visually similar images of wind-turbine-blade photos.

Next addressed is the second research question, "Can alternative-use concept generation be automated, e.g., by using visual similarity?" Computer-generated visually similar images are not subject to the fixating effect of pictorial examples to which humans may be susceptible, as seen in the concept-generation activities. To more methodically assess how VSI can support concept generation, these images may also be given to human participants as prompts for ideation. Such human involvement may improve feasibility of results, since VSI concepts presented here are simply visually similar to wind-turbine blades and not necessarily practical reuses. Selecting visually similar images to support concept generation can be informed by the optimal analogical distance between images and wind-turbine blades. Potential-reuse concepts with closer distances may lead to higher quality reuses and farther distances may lead to more novel reuses [26,27].

Also addressed is the third research question, "How effective is, and what are the limitations of, the newly developed method for alternative-use concept generation?" Improvement over human-generated concepts by VSI depended on the specific wind-turbine-blade photo. The wind-turbine-blade photos were selected to diversify results by featuring different numbers of wind-turbine blades. However, the photos' background or context had more effect on the types of visually similar images than the features of the blade(s). Two photos (B and C) produced more prohibited reuses as wind-turbine and airplane parts, not only due to the visual similarity of the blades, but also due to shared background features. One photo (A) produced fewer prohibited reuses, supporting that the choice of photo can reduce unusable results. This study revealed that photos with unusual, yet visually distinct backgrounds are the most promising for VSI.

Reuse of other objects may also be explored by applying this method. Future work extending the use of visual similarity by image recognition can apply these findings to inform the selection of source photos.

8.2 Screening and Evaluating Future Reuse Concepts. Since large volumes of potential-reuse concepts are possible using VSI (i.e., up to 100 per photo using Bing's Image Search API and potentially more using an alternative method), an initial screening process is desired, where measures to narrow a large pool of early-stage ideas may be relevant [28]. Visualization-based tools in sustainable product design can visually de-emphasize uninteresting results according to designer needs, to focus on more desirable designs in a large collection [29]. Finding promising photos for both the VSI source and output may benefit from tools such as ShapeSift, which uses the sketch-based input to select from a repository of past designs based partly on shape similarity to the input [30].

Future work may incorporate different measures of assessing concepts beyond those used in this analysis. These may include usefulness [31] and potential environmental impact [32]. Such measures are relevant in assessing practical and sustainable reuses of wind-turbine blades, which currently lack sustainable end-of-life solutions.

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Appendix A: Instructions Given to Concept-Generation Activity Participants

Instructions given to CGA-1 participants at Oldenburg University:

Identify how to reuse each of the parts shown in the following pages.

You should maximize reuse of each part, which are made of fiber-reinforced composites that have high strength and stiffness and low density.

You may further cut the parts but must minimize the amount of cutting needed. If you do cut the parts, mark where these cuts are on the views.

Instructions given to CGA-2 participants at Bremen University:

In the following pages, identify how to reuse each of the parts shown (one part per page).

Note that for safety reasons, such parts may not be reused in wind-turbine, airplane, or similar applications.

You should maximize the amount of the material reused for each part, which is made of fiber-reinforced composites (high strength, high stiffness, and low density).

You may further cut the parts but must minimize the amount of cutting needed. If you do cut the parts, mark where these cuts are on the views.

On each page, the same part is shown in three different orthogonal (top, front, and side) views and at least one isometric view. In addition, if the part is hollow, an isometric view of the part cut in half is shown.

A human scale (enlarged), shown below, is used to convey the size of the part on the isometric views.

Appendix B: Frequencies of Concept-Generation Activity Concepts With Duplicates Included and Removed

Table 8 Frequencies of CGA concepts

	No. CGA-1 concepts with duplicates:		No. CGA-2 concepts with duplicates:	
	Included	Removed	Included	Removed
Unidentifiable	24	24	18	18
Identifiable	138	108	124	118
Total	162	132	142	136
Prohibited	49	34	4	2
Allowed	89	74	120	116
Total	138	108	124	118
Shrunk	15	15	9	9
To-scale	73	58	110	106
Enlarged	1	1	1	1
Total	89	74	120	116
Infeasible	15	15	20	20
Low	9	9	16	16
Moderate	17	17	39	38
High	48	33	45	42
Total	89	74	120	116

Appendix C: Concept-Categories Frequencies and Examples

All categories listed exclude unidentifiable, prohibited, shrunk, and infeasible concepts.

Table 9 Frequencies and examples of recurring common categories of concepts

Category (total number of reuses, duplicates included)	Number of reuses from each source (examples, where more specific than category)				
	CGA-1	CGA-2	Photo A	Photo B	Photo C
Recurring across CGA only					
Art (4)	2	2			
Industrial (4)	3 (industrial funnel/mixer/mold)	1 (industrial fluid mixer)			
Mounts for Solar panels (3)	2	1			
Recurring across VSI only					
Wall (not buildings) (4)			1	3 (various barriers/border)	
Tank (3)			2		1
Recurring across CGA and VSI					
Building (73)	12 (roofs, walls for buildings)	12 (building façade, roof, shed, wall)	30	5	14
Water (31)	13 (water collection/ direction/ retention devices)	10 (flood prevention, reservoir)	1 (dam)	7 (embankment, flood protection structure, harbor wall	
Walkway (30)		3 (bridge, walkway)	11 (different photos of walkways)	15 (bridge, road)	1 (bridge)
Play (28)	15 (playground use, see-saw, slide)	10 (skate park, slide, swing)	3 (skate park, play dome)		
Fence (24)	10	3	10	1	
Vehicle (20)	3 (boat, train)	8 (boat hovercraft, race car, rocket, train)	6 (rocket, different automobile bodies)		3 (boat, truck)
(Overhead) Cover (18)	4 (shelter)	5 (bus shelter, shade)	4 (shade, shelter)	5 (hangar, roof, shade, shelter)	
Large container (9)		3 (for shipping, trailer)		2 (trailer, carrier)	4 (storage unit, trailer)
Flooring (8)		2	5 (pool deck)	1 (pool deck)	
Infrastructural (8)		2 (road barrier, road bump)		3 (road/highway barrier)	3 (overpass)

Table 9 (Continued)

Category (total number of reuses, duplicates included)	Number of reuses from each source (examples, where more specific than category)				
Pipe (8)	1	6 (water pipe)			1
Machinery (7)	1 (pump)	2 (car part, turbine)	1 (engine)		3 (pressure vessel)
Bench (7)		4 (public seating)	2 (bleachers)	1	
Material (6)	2	2			2 (composite mat, building structure)
Sign (5)		3 (billboard)	2		
Sports (4)		1 (ski hill)	3 (use in various courts)		
Boat component (2)	1 (sail)				1 (carbon-fiber mast)
Weapon (2)		1 (torpedo)	1 (cannon)		

Table 10 Frequencies and examples of unique categories of concepts

	Source of reuses (total number of concept categories)				
	CGA-1 (18)	CGA-2 (28)	Photo A (18)	Photo B (11)	Photo C (13)
Number and (list) of unique categories of reuses from each source	4 (blade, chimney, pillar, wave maker in pools)	8 (furniture, tool, tunnel, cable routing, pole, screen, shutters, stairs)	3 (sand, tombstones, fountain)	1 (dock)	3 (rail car, tanker trailer, fracking tower)

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