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Adaptive Assembly of Found Objects: A Prototypical structure from Discarded Bicycle Frames

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Abstract

This paper presents a methodology for reuse of industrial artifacts in structural design, with a focus on discarded bike frames as case study. It negotiates between irregular material variation and modular design logic, using computational tools and low-threshold fabrication. Frames are 3D scanned, organized into a digital inventory, and algorithmically aggregated into 2-dimensional patterns. Physics-based simulations enable assemblies to adapt to unique geometric differences of each frame and to transform into curved, shell-like structures. A prototype of 16 frames joined with custom standardized connectors demonstrates feasibility, and reconfiguration. The study evaluates performance and outlines potential larger-scale applications, proposing a material-oriented method for structural and architectural design in which the specificity of reuse components is mediated with indirect design controls through digital tools.

Keywords: Building part reuse, inventory constraint design, discrete aggregation systems, geometry matching, design for disassembly, adaptive structures

1. Introduction / Context

In the context of increasing resource scarcity, circular strategies are emerging as novel design and construction practices which provide approaches to reduce both material consumption and construction's embedded energy (Temizel-Sekeryan *et al.* [1]). In this context, approaches for the reuse of individual building components and materials are rising to prominence in research (Santos *et al.* [2]). Such approaches have a large historical heritage, steeped both in the historical practice of *spolia*, where individual elements were reused to both provide functional capabilities, but even more symbolic and aesthetic expression, and in more recent experimental design practices, which rely on scarcity and waste reuse as a source for innovation in design research (Certain Measures [3]).

In recent years, this design approaches gained increasing significance in the context of computational design and digital fabrication, where such technologies could be applied to mediate the variability of reused components. Specifically, two separate research and design strands can be identified in this context:

- One, which might be identified as "design from waste", focuses on the reuse of different kind of waste, leftover materials, offcuts, or other elements with non-standard geometry (De Oliveira *et al.* [4], Devenes *et al.* [5]). In this context, the focus is placed on developing a design and fabrication approach which integrates the unique geometry of the elements into a coherent assembly (Cousin *et al.* [6]), often not considering the potential for further reuse of these elements. In this context, computational tools such as the Hungarian matching algorithm (Cousin *et al.* [6]) or adaptations of stock-constrained optimization (Brütting *et al.* [7], Eschebach *et al.* [8]) are used to find the best possible combination of elements in each assembly, trying to minimize waste and modifications to the elements.

- A second one, which could be defined as "design for reuse", focuses instead on the development of novel modular component, which could be reused in multiple cycles (Minunno *et al.* [9], Estrella *et al.* [10]), but are in most cases produced from new materials. In this context, computational tools which are often grouped under the umbrella of "discrete design" (Retsin [11]), can be used to generate reconfigurable assemblies from repetitive parts (Rossi [12]).

While both approaches provide relevant strategies to increase the applicability of circular methods in both design and construction, there is still a significant gap in the development of design approaches which aim at both reusing waste materials, while also creating reusable components from such materials which could be assembled and reconfigured in various cycles of use. Such approach requires to bridge between computational techniques aimed at maximising materials reuse with combinatorial design strategies, which allow to determine the reusability of given elements in different assembly configurations.

What this means is that novel hybrid computational techniques are required, able to mediate between the inherent complexity of reused components and the demands for standardization of modular and circular approaches.

2. Previous Research

The work presented in this paper builds on an existing design method for assembly of non-standard parts combining different computational tools and fabrication approaches. Previous applications include spatial constructions built from natural tree forks (Allner *et al.* [13]), and later further developed to assemble discarded bicycle frames into grid shell structures (Allner *et al.* [14]). The method consists of four subsequent steps:

1. Found artifacts are digitized using 3D scanning, and the resulting meshes are algorithmically processed through a custom Grasshopper process to generate simplified center-line models that are compiled into a digital inventory.
2. Then a layout of connections specific to artifact characteristics is defined on a representative placeholder part. Duplicates of this "proto part" are aggregated according to a predefined connection syntax to form a 2-dimensional periodic pattern using Wasp (Rossi [12]), an open-source plugin for combinatorial design for Grasshopper.
3. "Proto part" instances are replaced by original inventory items maintaining the pattern connection topology. The geometric variation of each part produces deviations and misalignments at the connections, dependent on the constellation, local differences vary.
4. A physics-simulation in Kangaroo3D (Senatore and Piker [2015]) is used to mediate these deviations. The part aggregation is translated into a kinematic mechanism, in which parts are defined as rigid bodies. At the connections co-alignment constraints are defined by using the connection graph retrieved from Wasp to keep the pattern topology consistent.

In previous studies on bicycle frame structures, the existing joint details in the frames were reactivated for connections in the structure. This concept was a logical use of existing potential and it allowed to use the native rotational movement of those details along with shifting along axes for geometry matching, but the fixed position of predefined joints proved to be a constraint that would limit the global part matching mechanism preventing connection alignment within acceptable tolerances, which are particularly tight when working with metals. One distinct constellation of 5 different frames could be assembled to a closed loop, but with additional interconnected parts to form a larger structure, constraints increased and even attempts to combinatorial optimization failed to overcome remaining mis-alignments. Furthermore, custom complex fittings were required for realization to compensate varying tube diameters and connection distances.

3. Method

Within the context of design methods for irregular inventories, this paper expands on previous case studies with repurposed bicycle frames. In the presented work, techniques are refined to resolve problematic issues of the specific case, particularly with regards to the tight tolerances of steel elements, resulting in a robust method combining low-threshold computation and simple means of fabrication.

3.1. Pattern Structure

Addressing the limitations in the previous studies resulting from the use of existing joints for part connections, a new design pattern and connection approach was developed to provide the necessary adaptability, allowing the integration of geometric part variation. In the new pattern variation, main connections are assigned along the top and bottom tubes, disregarding existing joint details. This allows for flexible positioning of connections and translation of adjacent parts along tube axes. Additionally, parts are connected at the rear axle. The shifting possibility at the main connections in combination with rotational freedom significantly improve the global part matching mechanism (Figure 1).

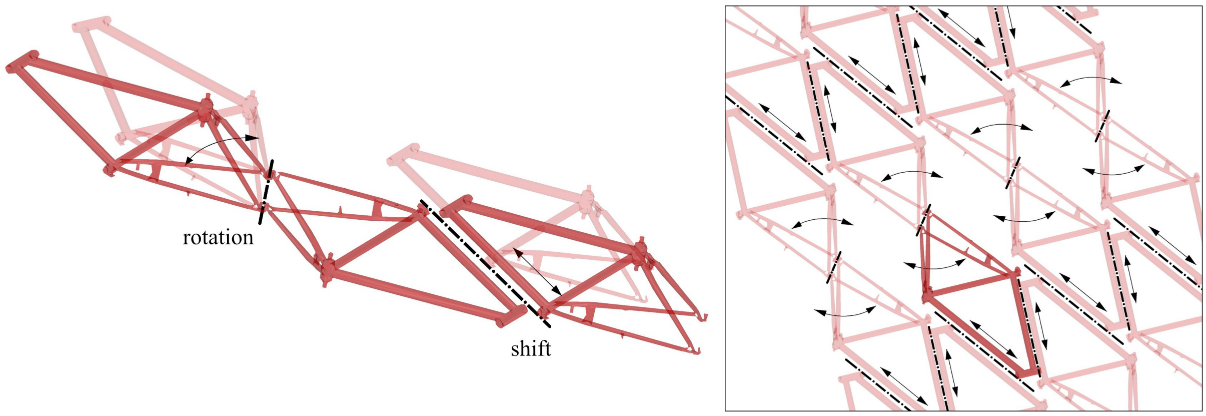

Figure 1: Connection mechanisms and aggregation pattern

In comparison to the previous pattern variations with more constrained mechanisms, this pattern structure is more adaptive to part variation. From a set of 18 frames, that had been acquired for previous studies, any combination of 16 parts can be assembled with alignment deviations below 1° (Figure 2).

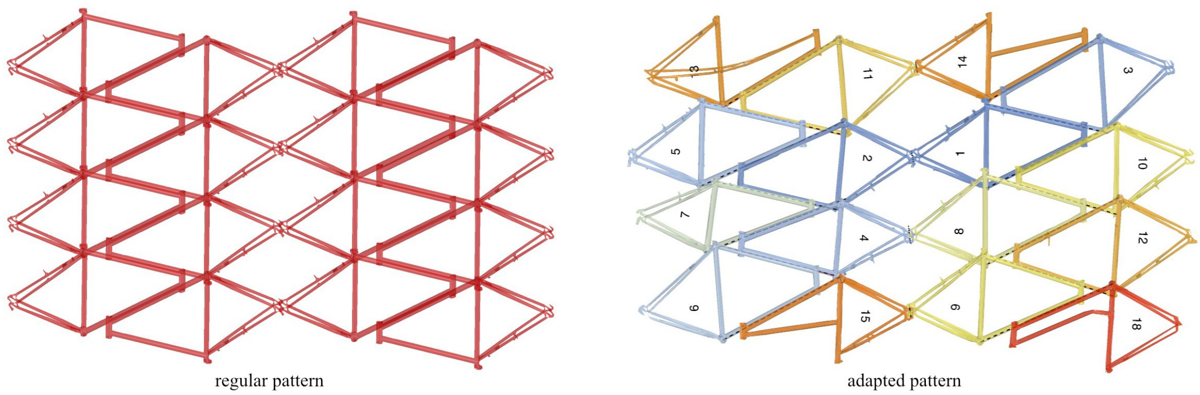

Figure 2: Pattern adaptation

Because all joints are hinges and the main tube connections align along relatively parallel axes across the pattern, global deformation can be inscribed into the structure in cross direction to connection axes but remains stiff along connection axes. (Figure 3).

3.2. Design System

The transformation capacity of initially flat structures into curved assemblies is the most significant characteristic of the design system and perhaps critical to make this concept practical for possible architectural applications.

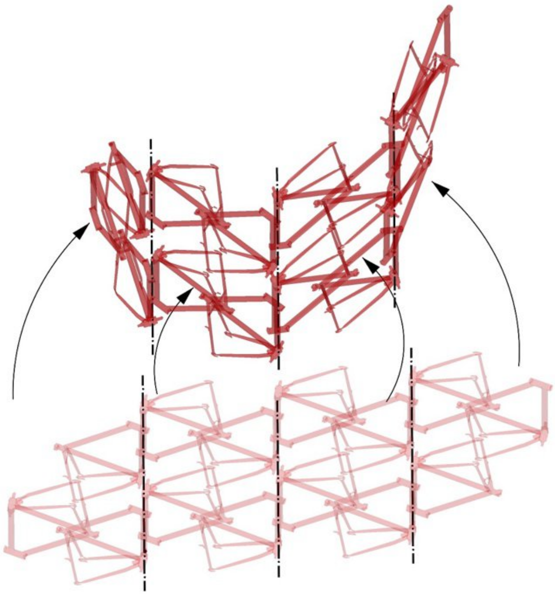

Figure 3: Curvature mechanism

To demonstrate the variability of this capacity, a consistent rectilinear patch of 48 bicycle frames is simulated and bent into different configurations. To simulate deformations in the digital model, additional forces are applied to the physics-simulation at the end of the aggregation process pulling parts to a user-defined design surface. This external transformation has only marginal effect on part matching within the structure: in different form configurations, deviation values remain relatively consistent (Figure 4).

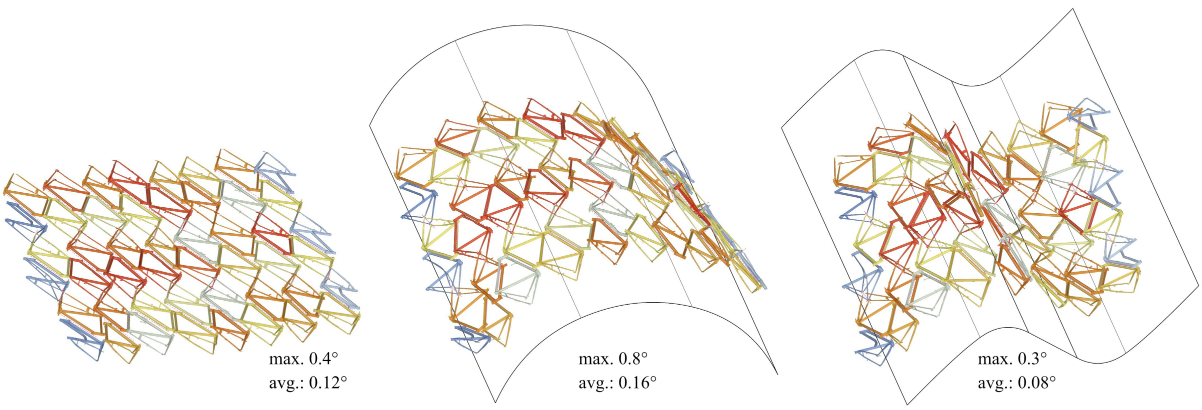

Figure 4: Form variations of an identical constellation of frames with alignment deviation values.

In relation to the aggregation plane, connected parts are stacked vertically to avoid collision of extending details on the frames such as the saddle post fixture. With this relative part positioning a max. range of folding angle between 42° and -72° on average becomes possible, which sets the fundamental parameter for deformation that can be inscribed across connection axes. Along this direction the structure behaves soft, and deformations can be distributed continuously to approximate a curving surface or alternated with flat angles to form a folded configuration, this could be described as the “design direction”. The opposite direction along main connection axes has a higher bending resistance and could be described as the “structural direction”. This stiffness effect is enforced by the respective wave amplitude inscribed along the “design direction” which amplifies the structural height of the overall construction. Respecting the guiding principles of cross-oriented design, and “structural directions” as well as the bending angle spectrum for each connection, a variation of bent forms can be created. The possible form vocabulary can range between three basic extremes, each possible as a curved or folded variation: 1.) Flat state, 2.) Vault, and 3.) Undulating state (Figure 4). Each variation could be envisioned in different architectural scenarios for example as a roof structure in horizontal orientation, or as a facade structure in vertical orientation.

Structural evaluation of two exemplary geometric configurations in Karamba3D (Preisinger [16]) suggests a potential for application eg. in light-weight roof constructions. The simulation also indicates that overall curvature contributes to stability due to its increased structural height. In the flat configuration deformation is stronger and in peak stress areas, part utilization is nearly double (93.8%) compared to the curved variation (56.4%) (Figure 5).

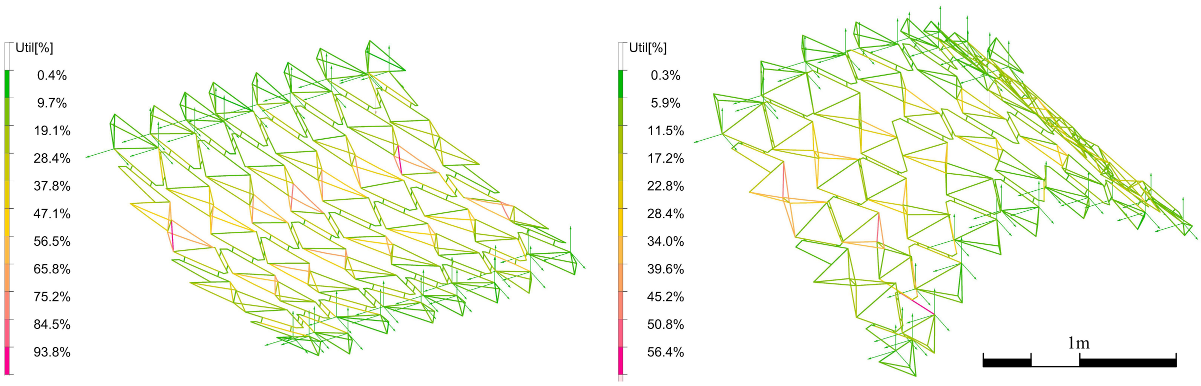

Figure 5: Structural analysis with Karamba3D for flat, and curved configuration
(models with hinged connections, displaying utilization under 2x dead weight, deformation scale factor 10)

4. Prototype

From the set of available steel bicycle frames 16 are assembled into two variations of a demonstrator structure to test the feasibility of the digitally developed system.

4.1. Connections

To realize the connection of parallel tubes, we found heavy weight pipe fixing collars to be a re-usable off-the-shelf industry product to improve the custom and laborious fabrication of details used for the previous bicycle frame prototype (see 2. Previous Research). Conventionally, these connectors are used to fix piping and other profiles to walls and ceilings for technical equipment in buildings. Among the different available formats, we found a product made from two identical parts of 3mm galvanized steel for pipe diameters from 32-34mm most suitable for the range of available steel frames with varying tube diameters between 30-35mm. For joining two tubes of adjacent bicycle frames, additional spacers were required. These were fabricated from five layers of 10mm birch plywood laminated to blocks. To ensure a close fit and high friction across all available frames, three variations with interfacing diameters of 30 and 35mm were produced using standard Forstner drills. These spacers enable to set a constant distance between all connected frames and allow the use of identical length bolts for tightening. (Figure, 6 left)

For each joint, two such connectors are placed along tubes to allow the translation of bending forces. Initial tests with additional rubber inlays (cut from an off-the-shelf non-slip mat for car-trunks) showed that resistance against rotational movement along tube axes could be improved to stabilize a position (under self-weight), but due to the leverage of the entire bicycle frame, not enough friction could be applied to prevent folding when applying additional force as it would be the case in a construction context. At the rear, always two frames are joined at a shared axis making use of the existing details for the wheel fixture. M10 threaded rods are the consistent standard for bicycle wheel axles across different types and sizes, which makes it possible to use the same standard for joining frames of various types. The two rear triangles are the weakest profiles in a bicycle frame, but with the connecting rod they form the edges of a flat tetrahedron—a stable structural unit. The smaller profile diameter is compensated by their triangular geometric configuration. The attachment of another bicycle frame adds another tetrahedral unit further stabilizing the structure in these locations (Figure 6, right).

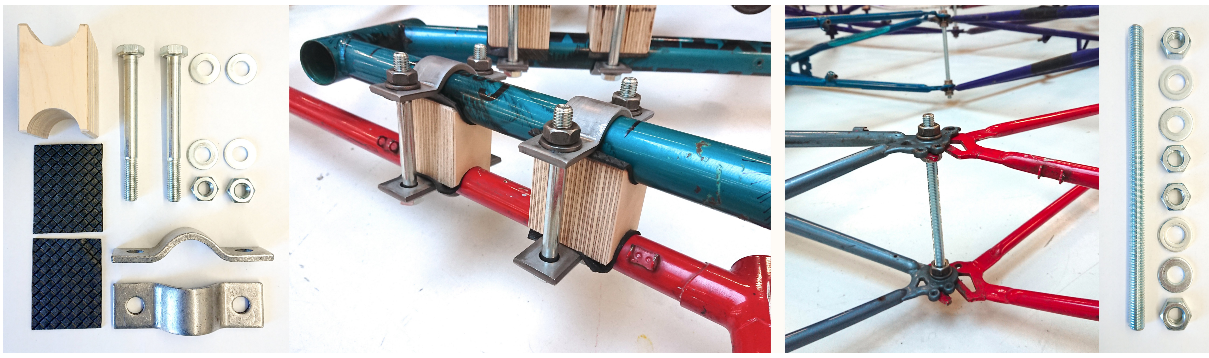

Figure 6: Custom standardized tube joint (left) and rear axle connection (right)

4.2. Assembly

Because this specific pattern uses top and bottom tubes for connection, only diamond frame types can be used. 12 of the 18 inventory items are of the diamond type, the remaining 6 step-through frames can only be positioned at the pattern boundary where no further parts are attached. First, a random constellation of those 12+4 frames as a flat pattern aggregation was set up digitally. Due to the adaptability of the pattern to compensate part variation, part combination did not have to be optimized first to improve connection alignment, as any (random) constellation would work.

4.2.1. Flat and curved variations

Then the respective parts were placed on the ground in the correct positions. Based on the chosen configuration, connectors positions for each joint were extracted from the digital model and marked on each (physical) frame. Lastly, connectors were placed and the parts assembled in place one-by-one, first with loosely tightened connectors to allow repositioning before tightening all joints.

In a second test, the structure was placed back on the ground, and all connections were loosened. Starting from one edge every connection was folded as much as possible before being re-tightened to fix each part position within the resulting curved overall configuration.

4.2.2. Pattern variation

For another experiment, the structure was dismantled and bicycle frames reconfigured. The goal of this exercise was to test a variation of the pattern in which frames are shifted along connection axes until they connect to the next frame along the axis. This concept was first studied in the digital model with the same workflow as before, but with a modified connection topology. The modification creates short cuts in the pattern producing a topology with smaller cell sizes, which should be beneficial for overall stability. On the other hand, because each frame tube is used for two connections at each end (instead of one) overlap is minimal which reduces connection stability. The reduced connection overlaps and the tighter topological structure with more connections also introduce additional constraints, restricting the alignment mechanism. For this pattern variation there are only a few specific combinations of frames are realizable, in most cases at least at one connection gaps remain after alignment simulation that could not be closed with the same connectors (due to insufficient tube lengths). However, out of 20 random combinations of 12+4 frames we found one that seemed realizable. Physical fabrication was more challenging than before because of minimal connection tolerances and because the structure could only be assembled in a specific folded 3D configuration required to close all connection gaps. We succeeded to build the major portion but could not connect the last 3 frames without force. (Figure 7)

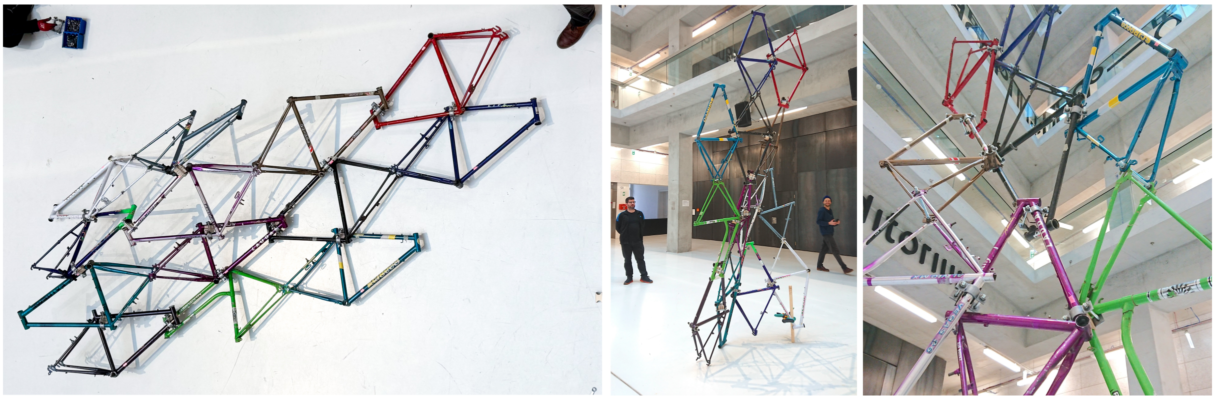

Figure 3: Folded configuration on the floor (left), in vertical position (middle), and in detail (right)

4.3. Evaluation

The partial structure of the pattern variation was rigid but more fragile. The negative effect of weaker connections with only one connector each, and minimal alignment tolerance dominated the presumed positive effect of increased stability through a denser topology. The failure of this experiment shows that in a system with irregular reuse parts, flexibility and robustness through higher tolerances can be more important than a structurally superior geometry of a system.

The flat and curved configuration of the initial design exhibited a high degree of stiffness and could be lifted and carried by four people without major deformations during transport. As a first test, the structure was placed in horizontal orientation on linear supports along the edges in "design direction", using the opposite "structural direction" to span between supports 2.2m apart. To verify the stability of the assembly, researchers of ~50kg and ~80kg body weight sat and hung on the center of the structure, which had no major deformation effect, as the structure remained stiff (Figure 8).

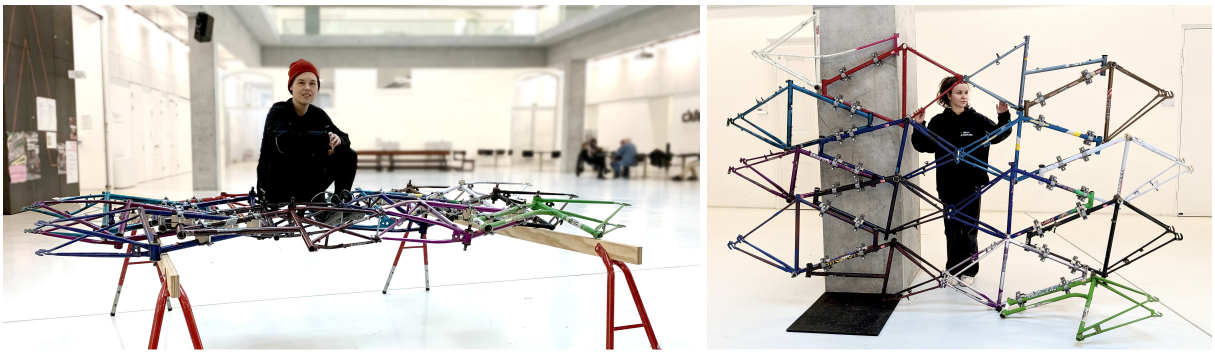

Figure 4: Load bearing assessment of horizontal flat assembly (left), same assembly in vertical position (right)

In the second test, after folding the structure into a curved shape, it was also placed onto linear supports attached at the same locations with the curvature facing upwards. This time, additional support elements were needed to adapt to the curving profile at the supports and to minimize forces in the direction of curvature ("design direction"). The structure seemed more stable with its increased height and handled the dynamic force of a climbing researcher of ~70kg body weight with no noticeable deformation (Figure 9). The structure was not tested to the limits to prevent damaging the bike frames.

Figure 5: Curved configuration in detail (left), and in horizontal setup for dynamic load bearing assessment (right)

5. Evaluation / Conclusion

5.1. Case Study

With the proposed pattern design system, both problems of custom connector details, and over-constrained alignment mechanism in previous versions of bicycle frame structures are overcome. The specific pattern design presented here furthermore allows for a plastic design flexibility enabling the adaptation to a variety of application scenarios but could also be used to activate the structure's overall geometry to contribute to structural performance. . The structural simulations show an applicability in lightweight roof structures. The curved configuration with a span of ~4.5m returns a utilization of under 60% at double self-weight which also suggests that other structural scenarios would be possible. However, due to the fixed part size, the scalability of this structural system is approximately limited to spans below 10m, dependent on the scenario.

It must be noted that the proposed system is limited to be applicable to steel bicycle frames due to the need for crack resistance and sufficient material thickness to distribute stresses at the joints. With wider connection fittings, aluminum frames could be implemented as well. To maintain the use of uniform connectors and a limited amount of spacer geometries, tube diameters are limited to a range between 30-35mm in the current setup. However, this does not constitute a system constraint, as additional spacer variations could be manufactured to accommodate for other tube diameters.

5.2. General Methodology

This paper demonstrates, how a radical reuse concept implementing non-architectural artifacts can lead to a productive design method with which the specific potential (geometric, structural, and aesthetic) of waste artifacts is activated to inform non-normative but functional design scenarios. This material dependent innovation effect is an important benefit of reuse projects that lies beyond resource and energy conservation. With the presented pattern method, resource specificity of found artifacts can (also) be implemented into a fully modular system (with standard connectors) that is de-mountable and re-configurable, leaving all parts unchanged and intact. Thereby two usually separate approaches, the reuse of irregular parts and versatile modularity, are combined in an adaptable system, that allows design freedom for modifying the overall form. . However, finding adequate alternative artifacts that combine structural performance, topological similarity and (local) availability is a challenge and may be critical for a practice-oriented generalization of the proposed methodology.

Despite this, the design system still proposes a practical and low-threshold hybrid workflow for experimental design-build work, applicable in a wider context. The digital tools used are well established in the design-make community, accessible with basic visual programming abilities. While the current workflow makes use of the closed-source Artec3D scanning environment, the system itself does not rely on high-resolution surface data. Alternatively, freely available photogrammetry tools could provide sufficient geometric information for the required center-line abstractions, thereby further increasing accessibility and reproducibility. Physical production exclusively relies on low-tech tools and simple assembly operations. This enables the workflow to be scaled and adapted to locally available materials and fabrication constraints without the need for high-end automation.

The Rhino/Grasshopper definitions used for the design of the presented structures will be freely available for download on the projects own online repository [17], with the goal of encouraging further experimentation and expanding the catalog of possible material and geometry typologies.

6. Outlook

Projecting the system into a scaled-up production within our Central European context, the currently used plywood spacers, that require substantial manual labor to produce could be substituted by injection-molded parts from recycled hard plastics. For fully operational architectural scenarios, support details would have to be developed to attach the structure to complementary building elements or structures. Cladding is another issue to be solved, membranes are an option, but the modular nature of the system would possibly also allow to integrate serial overlapping panels, using the existing pipe collar connectors for attachment, or reactivating the existing frame joints of the bikes.

For a more holistic evaluation, a Life Cycle Assessment would have to be conducted that compares a distinct bicycle frame construction with a structure from standard steel profiles in similar dimensions and structural capacity.

In future research, the proposed pattern method could be generalized and adapted to other artifact types. Using the same method of discrete part aggregation combined with constraint-based form finding in a physics simulation, structures from other predefined parts with varying geometry but identical topology such as trusses from deconstruction, or panels with reinforced edges could be reused as structural elements not only conserving gray energy and embedded structural capacity (otherwise lost in conventional recycling) but allowing their unique characteristic to influence the respective design scenario.

7. Acknowledgment

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