

An ephemeral, kinematic pavilion in the light of assembly/disassembly and material use/reuse

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Abstract

In this paper, we address reducing material consumption, conscious material selection, taking advantage of upcycling opportunities, and considering the reuse of components after the structure's end-of-life in the context of ephemerality. We observe the realized Zero Gravity Pavilion through the lens of (dis-)assembly and (re-)use. The pavilion is presented as a showcase for the responsible design of lightweight structures, in which the geometry of the overall structure and all its components serves as a mediator between the specific material properties and the specific structural requirements of a kinematic structure, and simultaneously enhances both functionality and its spatial effects. The pavilion is a light, kinematic structure and architectural space, which has been assembled, disassembled and reassembled several times in different locations, where it has been continuously modified and adapted. Thus, ease of assembly and rapid disassembly, as well as reuse of components, presented challenges from the beginning of the design process but also triggered ultimately simple solutions in detailing and fabrication. The entire structure is designed so that all components can be easily separated from each other. The paper analyzes and describes in retrospect how much of the material was processed from raw material, how much of them was (re-)used for the construction of the structure and how much of them could be reused after the final disassembly. Based on the total weight, 96% of the pavilion has been seen as reusable after all cycles of its use and its final disassembly. The presented study is considered a step towards a new perception of architectural aesthetics that reflects the responsible use of materials and prioritizes the question of how long structures should last to better shape our future built environment.

Keywords: structures and architecture, lightweight structures, ephemeral architecture, design for disassembly, wood, reuse, kinematic.

Use and reuse in the context of ephemerality

The concept of reducing material consumption, reuse, and repair is not new in the design of human-made goods. Although there are distinctive geo-cultural differences, reuse and repair were grown out of necessity in pre-industrialized societies and evolved as a tradition that was sustained by transferring the needed knowledge to future generations (Gerasimova and Chuikina, 2009). The loss of repairing and reusing practices seems to be reciprocal to the reorientation of society's mindset through wasteful linear production lines, mass consumption, and globalization. Today, in a period where we are paying back for all of these by global climate change and resource depletion, recent enthusiasm for reuse and repair practices is unavoidable, particularly in architecture and the built environment. Nevertheless, such concepts have not yet been addressed much in the context of ephemerality. In 1992, Lunt and Livingstone highlighted the early traces of consumer society based on rapidly decreasing quality in production, which consequently resulted in products with short lifespans. In architecture, short lifespans are often assigned to historical and present temporary structures, including the dwellings of nomads, shelters, stages at events and pavilions to answer temporal necessities. However, in the design of structures, the intended lifespan cannot be the measure of the demanded quality in design, detailing, and material, nor of its associated sustainability, as explained in the following paragraphs.

Instead of the common understanding of temporary, limited period of existence, Kronenburg (1995) describes being temporary in ephemeral architecture from the perspective of changing locations. Accordingly, a structure that has an ephemeral nature does not necessarily need to disappear in a brief time, instead, it can be disassembled, relocated, and reassembled several times, as in the case of "Cloud for fresh snow" (Klasz and Filz, 2015). On the other hand, the Multihalle Mannheim by Frei Otto, originally built as a temporary structure and still in use today, is indicative of a change in established perceptions of temporary structures. Likewise, Building 20 at MIT which was supposed to be demolished within two years after it was built, was in use for 55 years ("MIT's Building 20: The Magical Incubator," 1998). Those cases, among others, have been in use more than their initially intended service lives not only because of their resistance against the physical factors but also their inherent potential for adaptability, which is perhaps the key for overcoming human-related factors (Brand, 1994).

The physical factors are neither the only nor the essential reason for building obsolescence (Thomsen and Van der Flier, 2011). According to the studies conducted to investigate the demolition profile in Finland by Huuhka (2014), only 9% of buildings have been demolished due to physical factors. Most structures become obsolete, much sooner than they reach their service life. Given our dynamically changing and evolving needs, coupled with the environmental emergencies we face today, our society may need more flexible, adaptive, and adaptable structures and spaces (Markou et al., 2021), (De Temmerman et al., 2012) than ever before. In this context, we propose to consider ephemerality from the viewpoint of indefinite and transitory timelines, rather than from the viewpoint of short-lasting and long-lasting. Ephemerality together with lightness and adaptiveness, arguably, represent key qualities for being able to keep the architectural structures and spaces as long as necessary desired, or needed.

In the recent past, Rios et al. (2015) highlighted the designers' profound impact on generating barriers against reusability and recyclability by not considering the end-of-life scenarios from the early design phase. Compared to a destructive demolition process, design for disassembly (DFD) and design for deconstruction (DfD) offers benefits including enabling reuse and remanufacture of the individual components at the end of service life (Boothroyd and Alting, 1992), (William and Schouten, 2004). To promote the DFD and serve as a guideline for architects

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and designers, Crowther (2005), among others, compiled a list of principles based on the examples of the DFD approach in architectural history. The Crystal Palace by Joseph Paxton and Dymaxion House by Buckminster Fuller are representative icons of such mindset. However, nearly two decades later, it is still not a dominant approach in the building industry. While the environmental benefits of facilitating DFD are clear, Kanters (2018) brings up another aspect that concerns its possible adverse impacts on the architectural design process, such as restricting the designers' creativity. On the one hand, creativity is often associated with freedom, autonomy, weak or no rules, and few boundaries, but several studies suggest that particularly design constraints, often stimulate creativity rather than suppress it (Caniëls and Rietzschel, 2015). Instead of looking at DFD as a key design driver in a hierarchical parametrical design process, DFD, lightness, adaptiveness, and ephemerality may equally support each other in an integrated design strategy. From this framework, DFD includes the possibilities of repair and/or replacement of single parts as an aspect of maintenance and offers possibilities of reuse with regard to the consumption of raw material and the produced amount of waste. Here, it is worth mentioning the non-negligible environmental impact of the conscious selection of the used material (Takano et al., 2014), which is, according to our understanding, ought to be inherent in ephemeral thinking in architecture.



Figure 1. The Zero Gravity 2.0 Pavilion, a full-scale kinematic structure exhibited in Espoo, Finland. Photo credit: Lassi Savola.

As stakeholders in the building sector, we are responsible for initiating change to better shape our built environment ("Build Digi Craft," 2021), by influencing the industry and having a major impact on society and the future "Baukultur" (Swiss Confederation, 2018). The repercussions of giving materials and components a second life chance can trigger a change in the aesthetic perception of

professionals and society, creating an updated framework for immaterial values. There are many different and even controversial approaches to the topic of reuse. Ruan et al. (2021) built a trail prototype using wooden nails and salvaged timber material, from the cut-offs of a timber construction company. The ski grid shell by SXL (Colabella et al., 2017) was built from reclaimed skis, a material that was not previously considered for building. Euro pallets, for example, originally made for transportation and storing purposes, have recently been largely transformed into fashionable furniture. Their reuse as part of interior decoration was probably not even under discussion in the past. On the other hand, the Rock Print Pavilion (Gramazio Kohler Research, 2018) demonstrates a reversible building process, by using readily available materials, the string and small stones, so they can be reused for any other purposes after the current application. Brütting et al. (2021) present a computational workflow for a kit of parts approach, that allows the components to be reassembled in different configurations by using different holes of the produced, bespoke joints. The Zero Gravity Pavilion (Filz et al., 2019) (Fig. 1), features an integral design strategy mentioned above, which responds to the re-emergence of societies' interest in the necessity of less material consumption, repair, and reuse not least for reasons of economy and sustainability.

The Zero Gravity kinematic pavilion

The focus of this paper is to observe the realized Zero Gravity research pavilion, a full-scale kinematic structure, through the lens of (dis-) assembly and (re-)use. We do this in retrospect, as we developed and designed the structure on the premise that it is temporary, lightweight, structurally efficient, kinematic, and transformable, and can be reassembled in different locations for further experimentation and exhibition purposes. However, the questions of use and reuse were not the most driving design parameters in the development phase, but the main question of our retrospective investigations was to observe the use/reuse rate, which could be closely related to the above design aspects. Specifically, we are looking on the one hand, into the combined structural system of the individual components, and on the other hand, into the question of (re-)use, by examining how efficiently the materials were used and to what extent reuse was possible.

The presented experimental structure explores the Stewart Gough platform (SGP) (Gough and Whitehall, 1962; Husty, 1996; Stewart, 1965) as an architectural object with respect to the transformability of spaces while merging high-tech simulations and processes with low-tech production techniques and detailing (Markou et al., 2021). Such parallel robot mechanisms were originally developed for flight simulators. The motion is predicated on the movement of six articulated legs, which are connected to the moving platform and the fixed base plane by universal joints. The working principles of SGP and its diverse application space have been widely elaborated by Markou et al. (2021).

Kinematics in architecture by use of SGP was explored by the authors over the past 15 years (Filz, 2014, 2019; Filz et al., 2019; Filz and Naicu, 2015). The present design of the pavilion emerges from a multidisciplinary co-creation process that features artistic, kinematic, structural, and architectural qualities. Two groups, each of around ten students, from the Schools of Arts, Design and Architecture, and the Schools of Engineering were involved in the assembly and disassembly processes of the pavilion in 2019 and 2020. While the first group, undergraduate students, was involved in the project as a part of their synthesis studio course ARTS-ENG (Filz et al., 2021), the second group, graduate students, was involved as a part of the course Structures and Architecture: Informed Structures. Regardless of the level of the courses, both aim to lay the foundations for multidisciplinary, creative, and experimental thinking with a special focus on sustainability.

Since the pavilion was expected and planned to be disassembled and reassembled several times (Fig. 2.), ease of assembly and rapid disassembly have been considered from the beginning of the design process to the detailing and the fabrication. The entire structure is designed so that all components can be easily separated from each other. The structure's roof displays a super lightweight and highly efficient structure that ensures less material and energy consumption by simultaneously activating and utilizing specific material properties of plywood, such as flexibility (Table 1). Broadly speaking, reducing material consumption, taking advantage of upcycling opportunities, and considering end-of-life scenarios of the structure led to an understanding of the semantic potential of used materials. The resulting wooden pavilion creates a constantly transforming, ephemeral space for its visitors.

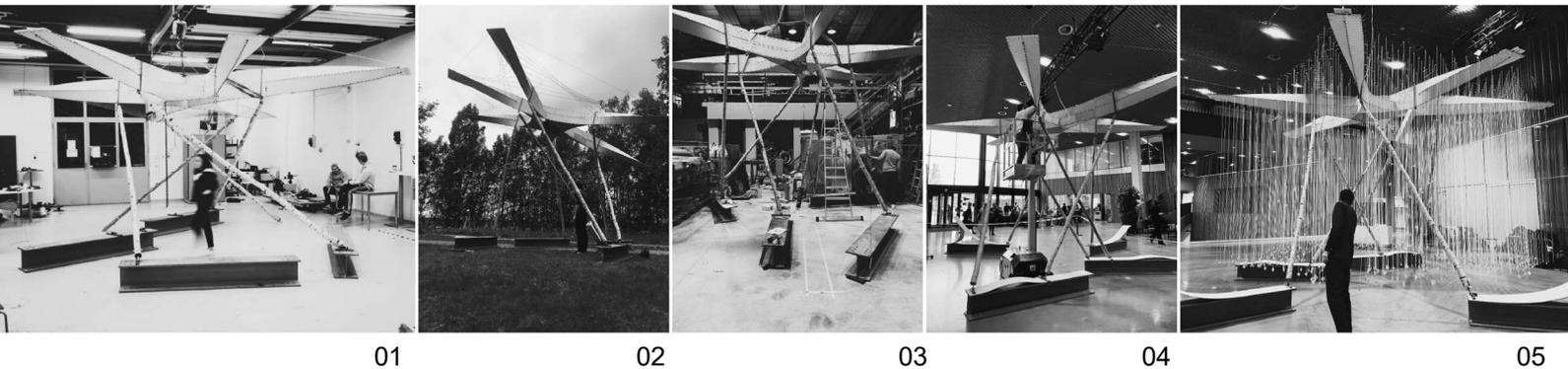


Figure 2. From the first assembly of the pavilion to the last. 01. the assembly in the lab, 02 the first exhibition outdoors, 03 reassembly of the structure with a different leg configuration, 04 the second exhibition indoors, 05 the transformation of the structure with suspended threads and leaves.

Assembly and disassembly of the pavilion's structure

The pavilion is composed of three main parts: (i) a moving lightweight roof, (ii) one linearly actuated and five fixed-length, hinged-hinged columns, and (iii) I-beams as the foundation (Fig. 1). The number of used columns was kept at the minimum possible, namely six, by considering the overall stability. Although stability could be achieved with a smaller number of columns by using fixed joints this was not applicable in our case because the connections must allow for kinematic motion, which relies on the SGP principle. Thus, the connection between the moving roof and the foundation is provided by the pin joints screwed at both ends of the columns, which also facilitate rapid assembly and disassembly. During assembly, the I-beams are firstly placed on the floor. Simultaneously, the prefabricated parts of the roof are assembled and the roof is lifted from the ground to hand level with a crane. Then, the columns are connected from their top end to the dedicated cantilever beams of the roof and the roof is lifted to its final position. Finally, the columns are connected from their bottom ends to the I-beams. The same sequence is followed in reversed order for the disassembly.

The articulated column allows a total length change of 1 m. Accordingly, all the columns rotate on their paths and the roof moves (translationally and rotationally) within the defined workspace. The realized configuration of the columns and the articulated column was determined considering architectural and structural requirements, among others, as described by Markou et al. (2021). However, by arranging the columns in different modes, different spatial configurations and different motion sequences can be achieved. Thus, the motion of the structure in its first assembly 01, as shown in Fig. 2, was not the same in its last 05.

Assembly and disassembly of the pavilion's components

A lightweight roof composed of structurally continuous plywood strips

Even though the roof of the structure forms a continuous flowing system (Fig.4), the components, namely the grid structure as the core (Fig.5 left) and the six

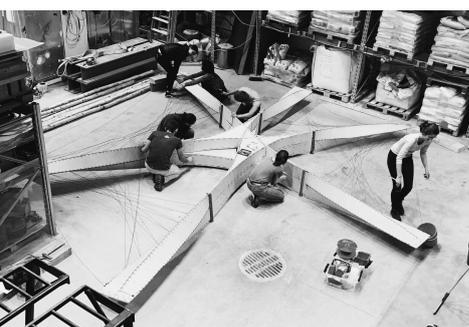


Figure 3. Assembly of the pavilion's lightweight roof from the torque-generated cantilever beams and the core.

cantilevers (Fig. 5 right), were prefabricated separately. The connection between the strips coming from the cantilevers and the grid structure was made by a bolted connection on an overlap area of 200mm x 250mm (Fig.6). Inspired by the gerberettes (Rice, 2017) of the Centre Pompidou, Paris, the connections were made on the segments of the roof, where the bending moment should be almost zero. As a design concept, the torque-generated cantilevering beams, composed of four strips, are decomposed into individual strips that intersect in the core and form further cantilevering beams in the system. The assembly model and the labeling of the individual strips were generated by following the same concept (Fig.4).

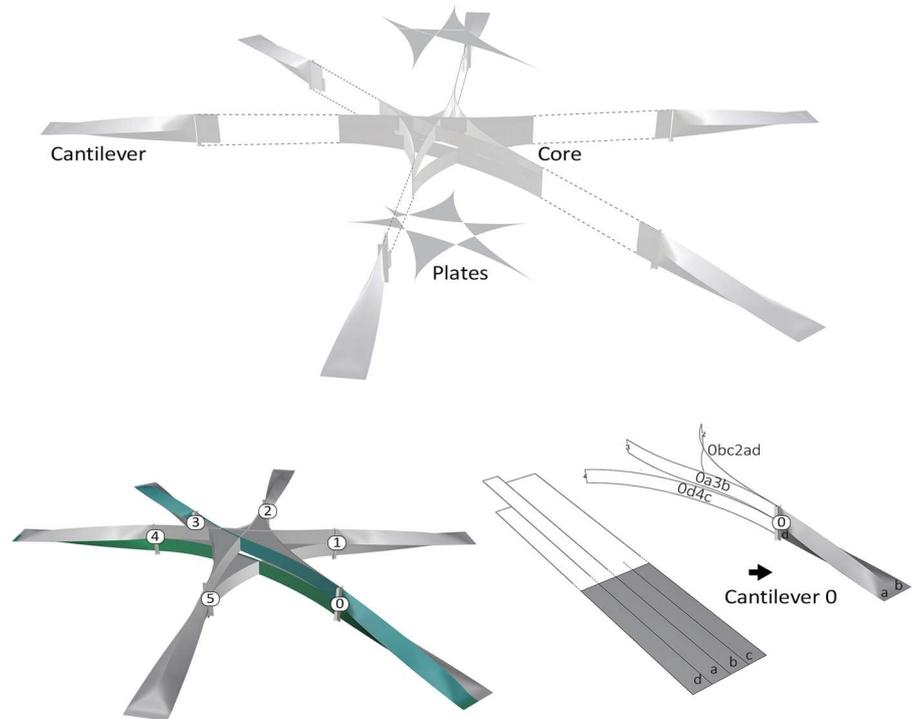


Fig 4. (top) The components of the roof from plywood sheet material, (bottom) structurally continuous strips and the assembly model of the strips coming from a cantilever and the core.

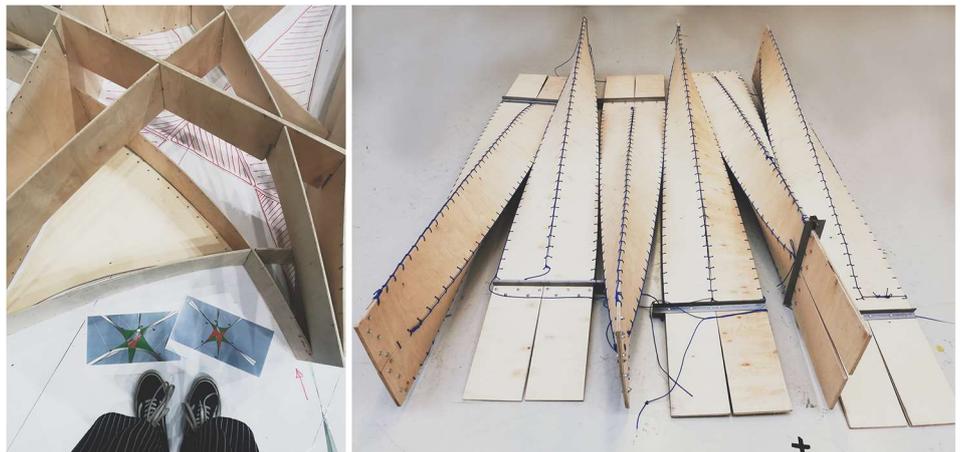


Figure 5. (left) The grid structure of the roof from actively bent plywood strips, (right) the rope-laced cantilever beams from actively torqued plywood strips.

Initially planar plywood strips were subjected to (i) active torsion and bending to form hollow section cantilever beams (Elmas et al., 2021) and (ii) active bending to generate the grid structure as the core of the roof (Fig 5). The flexibility of the plywood material was utilized by changing the geometry, correspondingly the

structural height, and residual stresses to achieve flexural stiffness following the force flow. In the core, the plug connection was used at the intersections of the actively bent strips without using any other fasteners or adhesive (Fig. 5 left). The slots were cut when the strips were in the planar state. The size of the slots was kept slightly larger to compensate the differences in the intersection angles due to bending. In this way, only two different sizes of slots were used. In addition, plywood panels were cut to match the curved shapes of the grid structure, which serve to brace and stiffen the core (Fig.4 top). The connection between these panels with the grid structure was made by lacing (Fig.7 left), inspired by the lacing pattern proposed for the assembly of the Z-Snap-Pavilion (Filz and Kumric, 2015).

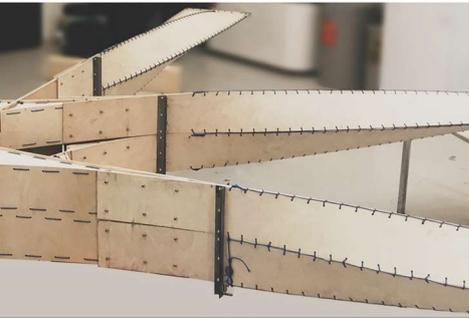


Figure 6. The bolted connection on an overlap area of 200mm x 250mm between the strips coming from the torque-generated cantilevers and the grid-structure.

For the assembly of the cantilever beams, the twisted plywood strips were clamped at their short edges (Fig.8 top). To create common seamlines along the longitudinal edges, we used “Clove Hitch End”, a friction-based lacing technique (“Clove Hitch,” n.d.). To do that, holes were drilled along the longitudinal edges of the strips where the rope was fed through. The rope locked itself by self-intersection instead of forming a knot (Fig.8 bottom). The low-tech lacing technique we used was chosen as the assembly method for several reasons: (i) it works like a hinge, (ii) it is not affected by the changing inclination of the joined twisted strips and the related material thickness conflict, (iii) it allows for following the curvature of the generated seamline, (iv) it is fully reversible, and allows for rapid closing, reopening, and adjustments. Being reversible allows a non-destructive disassembly process, which makes lacing as a commonly used technique in ancient wooden boat production (Creasman, 2013).

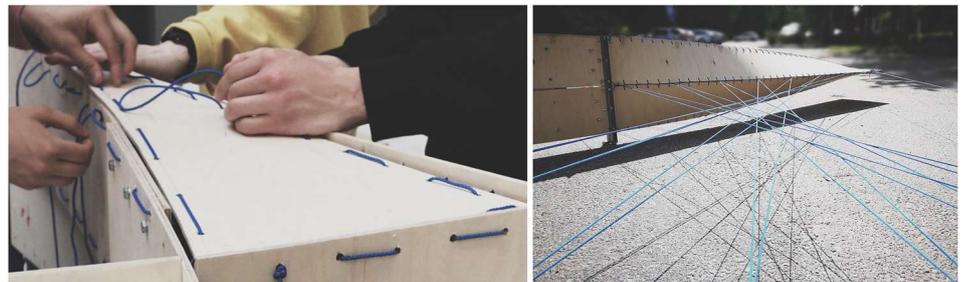


Figure 7. (left) Connecting the top and bottom plates with the grid structure by lacing, (right) tension ropes between the cantilevers.



Figure 8. (top) Twisted plywood strips clamped at their short edges before connected by lacing technique, (bottom) “Clove Hitch End” lacing/knot technique.

We also used ropes in a triangular pattern between the cantilevering beams (Fig.7 right) to provide in-plane rigidity of the cantilevers. The rope was fed through the laced seamlines of the cantilever beams without knots except at their very ends. In addition, an edge cable was used to adjust and keep the tips of the cantilevers at their predefined distance. The edge cable also guaranteed the stability of the roof in the absence of the triangular rope pattern. In this way, these ropes could be quickly replaced by a net structure during the exhibition time to allow a modification of the pavilion and its architectural space below the roof. The electrical and electronic components that we used to activate the servo motor for the roof’s motion were hidden in the boxes of the core’s grid structure. The cables were grouped together but not directly attached to the structure, so they were easier to separate during disassembly.

Columns and foundation

The steel fork elements of the roof (Fig.9 right top) were used as clamps for the cantilever beams, and as connectors between the roof and the columns. The pin joints screwed to the top end of the columns (Fig.9 right middle) connected to these steel fork elements. The pin joints screwed to the bottom end of the columns were connected to the metal connectors bolted on the I-beams, which serve as the temporal foundation for the structure and as benches for the visitors (Fig 9 right bottom). The metal connector was made from two pieces, while the

first piece, a rectangular tube, provides a bolted connection to the I-beam, the second piece, an L-shape plate, is used to connect the pin joints of the columns. Since the connector allows for enough play for the constant motion of the columns, we did not have to customize them individually according to the columns' different motion paths. No parts were welded directly to the I-beams; all connections were made with bolts and nuts using the existing holes on the I-beams.

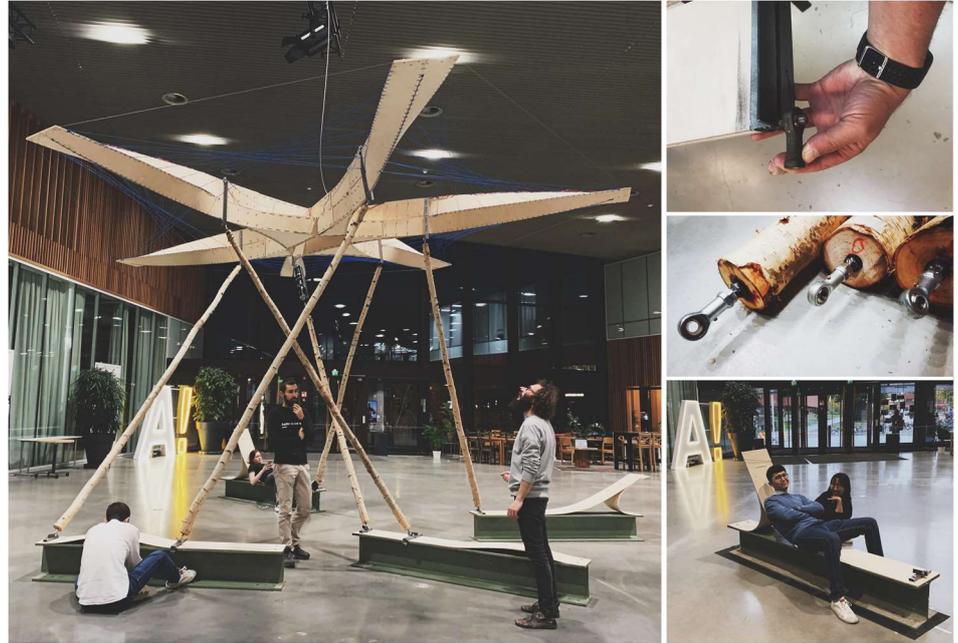


Figure 9. (left) The pavilion, (right top) the steel fork element connected with a pin joint, (right middle) pin joints screwed to the columns, (right bottom) I-beam serving as foundation for the structure and bench for the visitors.

In general, the specific material properties were utilized throughout the structure to meet structural and/or functional needs, as described in Table 1.

Roof (cantilever beam)	Roof (grid core)	Column	Foundation
	Lightness		Heaviness
Flexibility		Stiffness	
Cross section with high second moment of area for bending resistance	Cross section with high second moment of area for bending resistance	Circular cross section for covering all directions of loading	Planar top surface and appropriate dimensions for serving as a bench for visitors
Cross section with low second moment of area where min. bending moment expected to occur			

Table 1. Utilized material properties to meet specific structural and/or functional requirements.

The pavilion in the light of use and reuse

Although it would be interesting to trace the total carbon footprint of materials from the manufacturing process to our use (including packaging, transportation, etc.), this is not the main focus of our research. Therefore, we started counting

the waste metrics at the time we had all the materials in our lab. The percentage of those materials, which went directly into the structure, and which became waste due to the application-specific requirements or after the current application, was calculated. An overview of the results and metrics is shown in Table 2.

In brief, a total of 616 kg of material was either purchased or collected for building the pavilion. After deducting packaging, offcuts, etc., 607 kg were actually used for the realization of the structure, of which 77% came from salvaged material. After final disassembly, 96% of the material can be reused, which equals 591 kg.

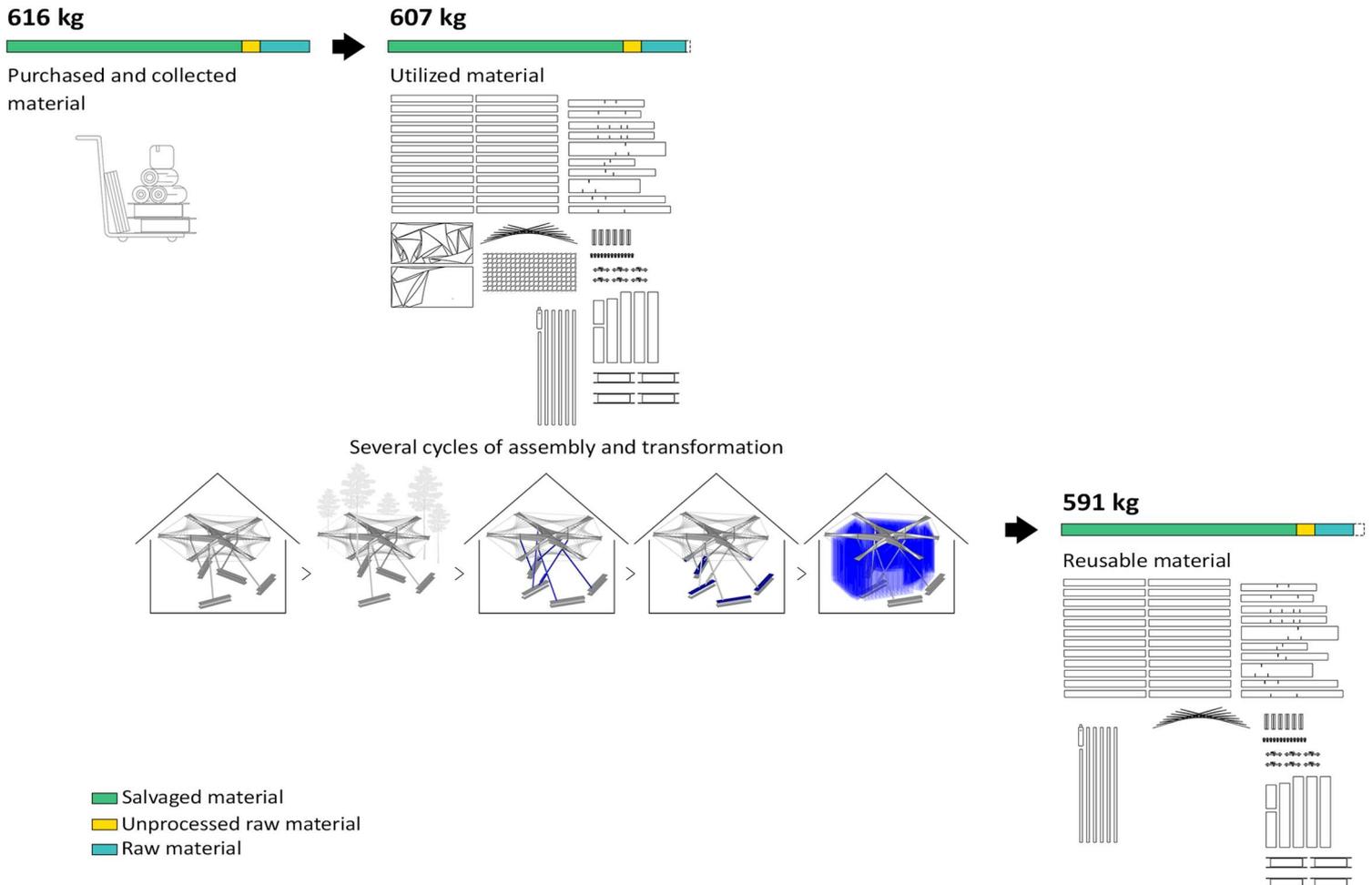


Figure 10. An overview of the used material, from purchasing and collecting for building the pavilion to the final disassembly.

The structure consists of components that were produced from raw material (Fig.11, p1, p2, p3, o1, o2) and others that were reused (Fig.11 p4, s1, s2, s3, s4). Reused components include I-beams, spherical pin joints, metal connectors, all screws and bolts, electric and electronic components including, servomotor and Arduino mounting plate, all of which can be again reused after the current application. In this framework our approach is exemplified by the I-beams: We borrowed the I-beams, which were in regular use in the testing hall of the Civil Engineering department’s laboratory at Aalto University. We selected I-beams for the structure because we identified them; (i) as heavy enough to serve as a temporary foundation, (ii) as small and light enough for transportation and adjustments to be made manually, (iii) for having ideal dimensions (seating height) to serve as benches, and (iv) ideal for clamping and attaching other parts to them. At the same time, we were not allowed to modify them because they went back to their original use in the lab. Thus, we were neither allowed to drill additional holes, nor to apply any chemicals, nor to weld anything on them. We

tried to take advantages of what we had at hand, accepted the given constraints, and adjusted our design accordingly.

Purchased and collected material			Utilized	End of life	
			[%]	Leftover	Reusable
Purchased [from raw mat.] 136 kg	Plywood 100 kg	Cantilever strips 50 kg p1	100 %		x
		Core strips 25 kg p2	95 %		
		Core plates 25kg p3	69 %	x	
	Unprocessed tree trunk 35 kg	Columns 35 kg t1	100 %		x
	Polyproplene 1.2 kg	Rope 1.2 kg o1			
	HDPE 0.2 kg	Net 0.2 kg o2	55 %	x	
Collected [mat. for reuse] 480 kg	Plywood 10 kg	I-beam covers 10 kg p4	100 %		x
	Steel 10 kg	Fork elements 6 kg s1			
		Pin joints 2.4 kg s2			
		Connectors 1.8 kg s3			
	Ready-made steel 460 kg	I-beams 460 kg s4			
Total weight 616 kg			607 kg		591 kg
The non-structural components of the pavilion used during the exhibition time, namely sheep wool yarn and the fallen birch leaves are not included in this weight calculations.					

Table 2. Weight calculations of the used materials including the percentage that went directly into the structure, became waste due to application-specific requirements, and considered as reusable after the current application.

The leftover plywood panels were utilized as seating for visitors and mounted on the I-beams. The steel fork connectors were produced by welding leftover L-shape profiles with a bolt between them. After the current application, the bolts were cut out of the profiles and discarded, but the L-shape profiles were saved for possible future use. Unprocessed tree trunks were used as columns without applying any chemicals or a debarking process. Consequently, they can still be considered raw materials even after several cycles of use (Fig.12). In short, all parts of the structure were either machined as little as possible or not at all.

For the realization of the roof, we used 6.5mm all-birch plywood, with low-tech detailing and a simple cutting pattern. The entire roof weighs less than 150kg and covers an area of 45 m². In total, we used 8 sheets of plywood, 75% of which are strips directly incorporated into the structure, without waste. After the final disassembly, the strips were either reassembled with different types of joints or/and used for further load tests for research purposes (Fig.12). The remaining 25% of the plywood material was used for the fabrication of the planar plates of the core, with the cutting pattern optimized to the format of the sheets to save material. Due to their application-specific shapes, these plates were not considered reusable after final disassembly (Fig. 11 p3). A multifilament braided

polypropylene rope with a diameter of 4mm was used for lacing the individual strips of the cantilever beams and as tension ropes in between them. Instead of purchasing packaged standard lengths, the rope was cut to 220m from the spools in the shop to minimize waste. After final disassembly, the rope was retrieved with ease, by removing the end knot, reeling the rope, and storing it for possible future applications. Even though a variety of ropes are available, the multifilament, braided polypropylene rope seemed to be an appropriate choice due to its lightweight and high strength, later verified during testing of the beam element. Additional advantages were its surface smoothness, which supported the lacing and tensioning technique used, and its stretch characteristics. In addition to meeting the above-mentioned requirements, its wide range of applications allowed for easy reuse after the current application.

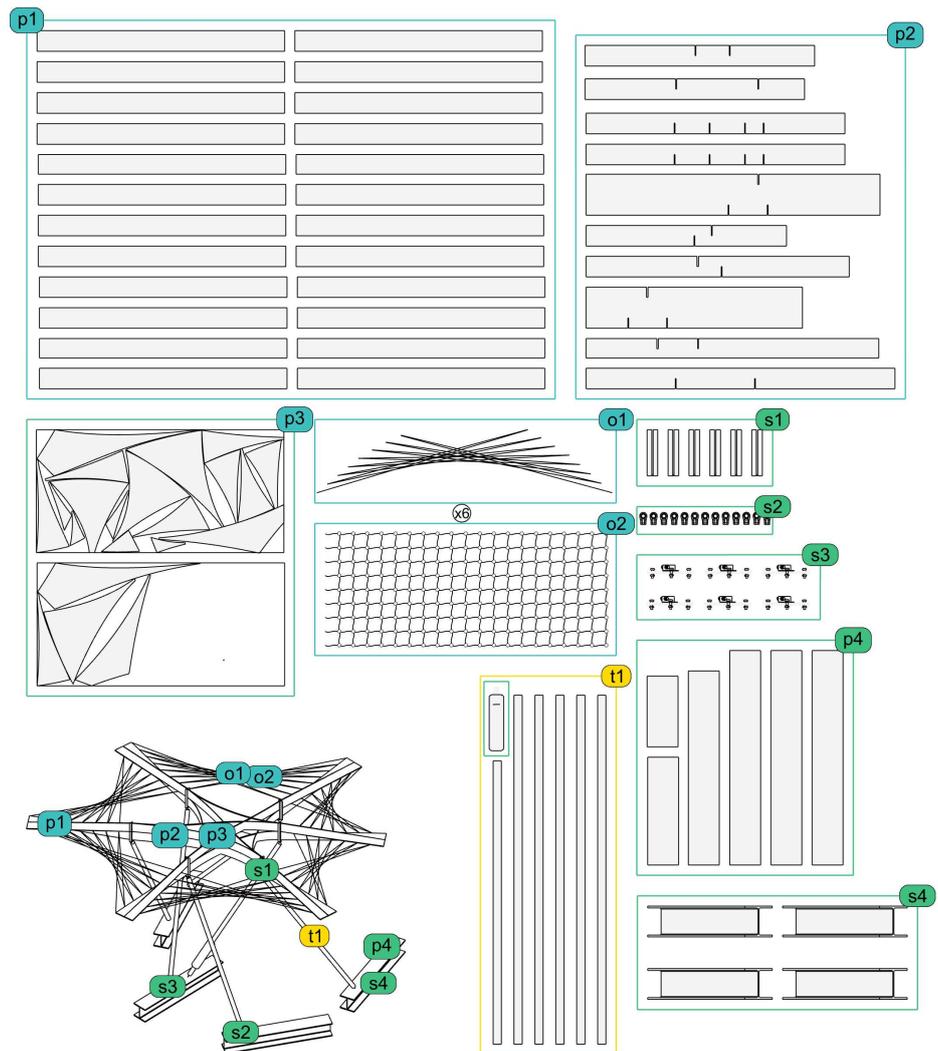


Figure 11. Pavilion's components from raw material (blue), unprocessed raw material (yellow), reused material (green). The non-structural components of the pavilion, namely sheep wool yarn and fallen birch leaves are not illustrated.

During the exhibition time, the pavilion was transformed into a more volumetric object. The tension ropes between the cantilever beams were replaced with a transparent, very thin bird protection net with a mesh size of 20mm x 20mm and an area of about 20 m². After the final disassembly, the net had to be discarded, because it was cut to fit between the cantilevers. It served as an almost invisible grid for the suspension of threads that visualized the volume of the pavilion while generating interior spaces. These non-structural components of the pavilion were

made of purely natural materials, namely sheep's wool yarn and fallen birch leaves (Fig. 13). We used them for artistic purposes, especially to visually translate the movement of the structure and the change of space, and to illustrate the concept of ephemerality to visitors with the "falling leaves". The cutting of the individual threads, thus their individual lengths, resulted from the collision of threads and the rotating tree trunks, similar to a Boolean operation. The fallen birch leaves were collected directly at the Aalto University campus and attached to the end of the free-hanging woolen threads. By twisting the yarn in opposite directions, the fibers were loosened, and the leaves were attached solely by friction, without glue or other mechanical fasteners. The spatially curved surface consisting of leaves virtually floated in space and brought an additional dynamic to the movement of the kinematic pavilion. The fact that over time a few leaves came loose and fell to the ground was part of the concept and amplified the ephemeral character of the structure and space.

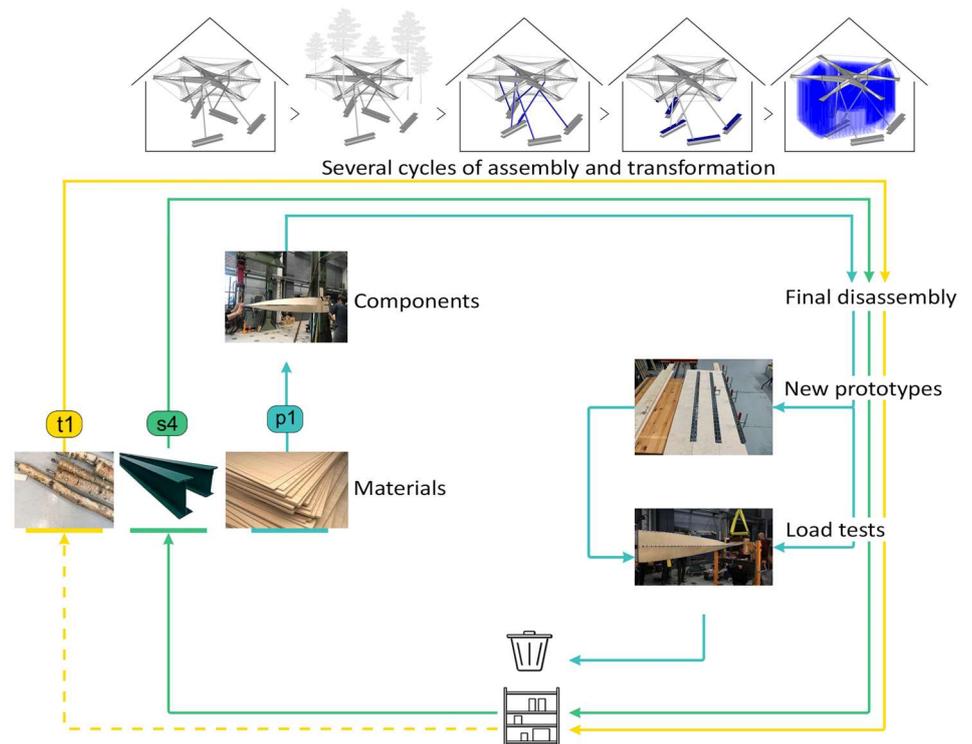


Figure 12. Life cycle illustration of the materials, material flow and logistics: p1 purchased plywood sheets, t1 unprocessed tree trunks and S4 borrowed I-beams from the lab.

Discussion, conclusion and outlook

Zero-Gravity Pavilion, the first of its kind. The presented structure of the Zero-Gravity Pavilion as a kinematic architectural space is the first of its kind and a variety of different questions had to be answered, including novel, extremely lightweight support concepts, predictability of kinematic movement, interaction with visitors and ease of assembly without heavy machinery. In the context of architectural discourse, the discussion of possible building envelopes is inevitable. Although this has been left out for the moment, our results allow very precise as well as partly speculative insights.

Use/reuse rate through all cycles. The Zero-Gravity Pavilion has been assembled, disassembled and reassembled several times in different locations. In retrospective, we answered the research question of this paper, namely, to investigate the use/reuse rate from the fabrication through all cycles of

transformations and uses, with concise calculations and an overview of materials and elements in terms of material use, waste, weight and by tracking the individual members during this time. Therefore, our paper analyzes and describes in retrospect how much of the materials were (re-)used for the construction of the structure and how much of them could be reused and recycled after the final disassembly. In conclusion and based on the total weight, 96% of the pavilion can be seen as reusable after all cycles and its final disassembly.

Detailing, ready-mades and modularity. During the aforementioned cycles, the pavilion was continuously modified and adapted in the sense that different aspects of motion and architectural space were brought to the fore. Zero-Gravity Pavilion can thus be seen as a showcase for the responsible design of lightweight structures, in which the geometry of the overall structure and all its components serves as a mediator between specific material properties, the specific structural requirements of a kinematic structure, and at the same time enhances both functionality and its spatial effects. In general, temporary structures seem to have great potential in contrast to permanent buildings in terms of the reuse of materials and components, not least due to the suitable details for quick disassembly and enabling to use of salvaged materials. Such structures increasingly make use of "ready-mades", as in the case of our structure the joints from the automotive industry or the I-beams as foundation and seating. Additionally, we recognized a transformation process in our and the students' thinking regarding modular construction, which should not be misunderstood with standardized and repetitive elements, members or modules. If, on the other hand, the elements are prefabricated as modules, both can be guaranteed: the quality of the elements and independence from weather conditions. These aspects also increase efficiency in terms of accelerated assembly times on site. Moreover, in the event of damage, certain elements can be replaced without affecting the overall structural integrity. All these aspects were taken into account and used during implementation.

Transformable and temporary vs. static and permanent. As widely discussed in the introduction, in the light of ever-growing sustainability problems we believe that in our fast-changing times, more transformable and adaptable spaces (Calatrava, 1981) will be needed in the future that go beyond flexible and movable shading systems while having less to no negative environmental impact. In the current work, we focused on our case study but did not compare it to other temporary or permanent structures or the general construction industry. A comparison of "permanent versus temporary buildings" from the perspectives of use/reuse presents an exciting future research question with the potential for great impact. Nevertheless, we need to question the common static thinking in architecture, where almost everything is dynamic, such as the seasons, the temperature, and human needs. As a possible real-life implication of the insights of the research on the Zero Gravity Pavilion, we envision inspiring architectural spaces that can change their shape and volume depending on the needs of the users or to reduce energy consumption during the seasons or when not in use. On the other hand, providing a possibility to disappear without leaving traces behind could have a huge positive impact on decreasing obsolete building stock. As in the case of our structure, 77% of the weight came from the reused materials, which were returned to their original purposes at the end of the pavilion's life, and 19% of the weight came from the raw materials, which were put on the shelves for future use, such as unprocessed tree trunks (see Fig.12 and 14).

Material consumption and pedagogical aspects. Reducing material consumption by designing lightweight structures and seeking upcycling possibilities can offer a new perception of architectural aesthetics that reflects the responsible use of materials. The design and build process of the Zero Gravity Pavilion follows a strategy for such a change, by involving diverse groups of students at Aalto University, future stakeholders of the building sector, with the



Figure 13. Visualization of the transformable space of the Zero Gravity Pavilion through hanging woolen threads and the falling yellow leaves. Photo credit:Lassi Savola.



Figure 14. Unprocessed tree trunk working as column. Photo credit: Lassi Savola.

pedagogic intent to highlight the aspects of lightness linked to structural geometry, ease of (dis-)assembly and (re-)use for the future building sector, society, and environment.

Logistics. Through the project, we also noticed the shortcomings of an assembly manual, which is key to allow for easy transfer of processes, sequences, and techniques for the reassembly and for minimizing the level of required supervision. Although the entire structure allows disassembly into planar and linear elements, which minimizes storage volume, denominating all parts and connectors is still a challenging aspect. In our case, it was easily solved by the available lab spaces at the university. However, transferring this idea into real-world applications that are dealing with larger numbers of elements and bigger scale, opens new questions with respect to logistics and proper storing but also regarding architectural qualities and aesthetics.

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