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# From nest to bridge: Exploring avian construction techniques for innovative architectural solutions.

Dana SAEZ*, Raman SULIMAN*, Matías LICHTENSZTEJN*[a], Santiago MIRET [a], Andrija Pranjic, and Martin TRAUTZ

*Chair of Structures and Structural Design (Trako), Faculty of Architecture, RWTH Aachen University
Schinkelstr. 1, 52066, Aachen, Germany
saez@trako.arch.rwth-aachen.de

[a] Chair for Morphology Arch. Lencinas – Faculty of Architecture, Design and Urbanism (FADU), University of Buenos Aires (UBA)

## Abstract

Objects in nature, whether animate or inanimate, carry a distinct form shaped by the material formation processes that define their creation. In the architectural context, humans have consistently found inspiration in these phenomena referred to as natural constructions, driving the pursuit of innovative technologies across epochs. This study delves into the intricate realm of natural organizations, focusing its investigation on avian nest constructions, in our case, the Chiffchaff's nest.

The Chiffchaff's nest serves as a case study, revealing a complex structure reminiscent of the self-supporting structure known as reciprocal frame (RF). Unlike conventional RP structures, usually designed for expansive central spans, Chiffchaff birds employ this technique on a smaller scale, gradually increasing the radius and stacking multiple layers to craft a self-supported overhang. This study calculates maximum overhang by incorporating the stacking problem (SP), offering nuanced insights into Chiffchaff's construction technique.

Moreover, this study aims to gain insights into model-informed avian nest constructions. Drawing from evidence-based protocols and rules, it employs 3D modeling to evaluate their physical integrity and spatial relationships. It seeks to discern the factors influencing structural morphology, identify construction rules for systematic reproduction, and reinterpret these findings to architectural-scale structures using visual-based programming tools. This approach translates the acquired knowledge into a self-supported cantilever construction system proposed for a pedestrian bridge.

**Keywords**: animal constructions, avian nest constructions, reciprocal frames, self-supported structures, stacking problem, structural morphology, self-supported cantilever, innovative architectural solutions.

## 1. Introduction

Humans have long sought inspiration from the natural world in the pursuit of architectural innovation. Natural constructions, shaped, for example, by the intricate processes of material formation, offer a wealth of insight into efficient structural design. Among these natural marvels, avian nests stand out for their remarkable complexity and adaptability. This paper explores the potential of avian construction techniques as a source of inspiration for innovative architectural solutions, focusing mainly on the construction methods of the Chiffchaff bird.

The Chiffchaff's nest is a case study due to its intricate structure, reminiscent of the self-supporting framework known as the RF. While conventional RF structures are typically designed for expansive central spans, Chiffchaff birds employ this technique on a smaller scale, ingeniously stacking multiple layers to create a cup-like, self-supported nest with overhang. This study investigates the Chiffchaff's construction technique, particularly addressing the stacking problem (SP) to calculate maximum overhangs and gain insights into its structural integrity.

Furthermore, this research explores the principles underlying avian nest constructions through evidence-based protocols and rules. By employing 3D modeling techniques, the study seeks to evaluate these structures' physical integrity and spatial relationships. Through rigorous analysis, the goal is to identify key factors influencing structural morphology and construction rules for systematic reproduction.

The ultimate objective of this study is to translate the acquired knowledge of avian construction techniques into practical architectural solutions. Leveraging visual-based programming tools, the research proposes a self-supported cantilever construction system suitable for application in architectural projects, particularly in the design of pedestrian bridges.

In summary, this paper embarks on a journey from the intricate world of avian nest constructions to the realm of innovative architectural design. Drawing parallels between natural and human-made structures aims to unlock new avenues for sustainable and efficient architectural solutions.

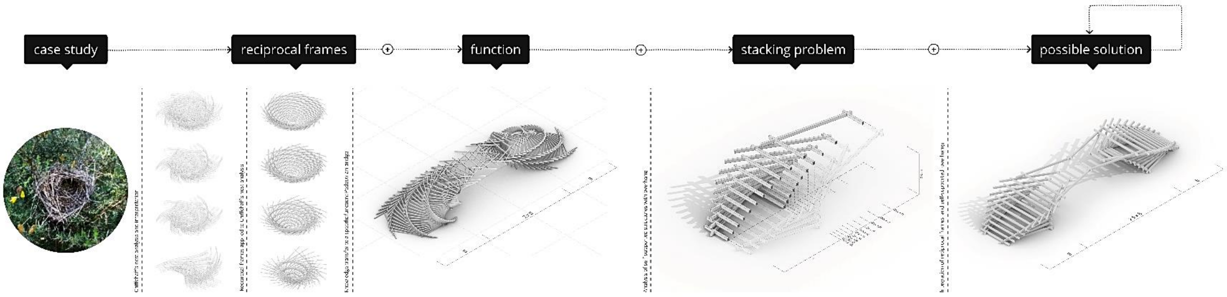

Figure 01: From nest to bridge

## 2. Methodology

### 2.1. Selection of Chiffchaff's Nest as a case study

This study examines the construction of Chiffchaff nests due to their complex method of assembly, which involves creating a complex structure from multiple smaller elements.

Notably, the arrangement of the nest components in Chiffchaff construction is not random; instead, it adheres to a set of logical principles, enabling the resultant structure to attain stability, comfort, and durability. The Chiffchaff selectively chooses the twigs suitable for use in its construction, positioning them where one end rests upon another, thereby fostering mutual support among the twigs and facilitating the formation of interwoven-like layers.

This construction logic was experimented with through Grasshopper (GH), and to study these nests in depth to understand how their structure works, it was decided to elaborate in a series of catalogs since the number of possible nest solutions using this system is infinite. Using catalogs made it possible to control the results and vary certain aspects gradually. Generating a catalog for design space exploration has proven to be helpful in this design approach. Similar use cases can be seen in the works of Greg Lynn in the publication "Greg Lynn FORM" [1] and in the works of Foreign Office Architects (FOA) in the publication "Phylogenesis: FOA's ark" [2].

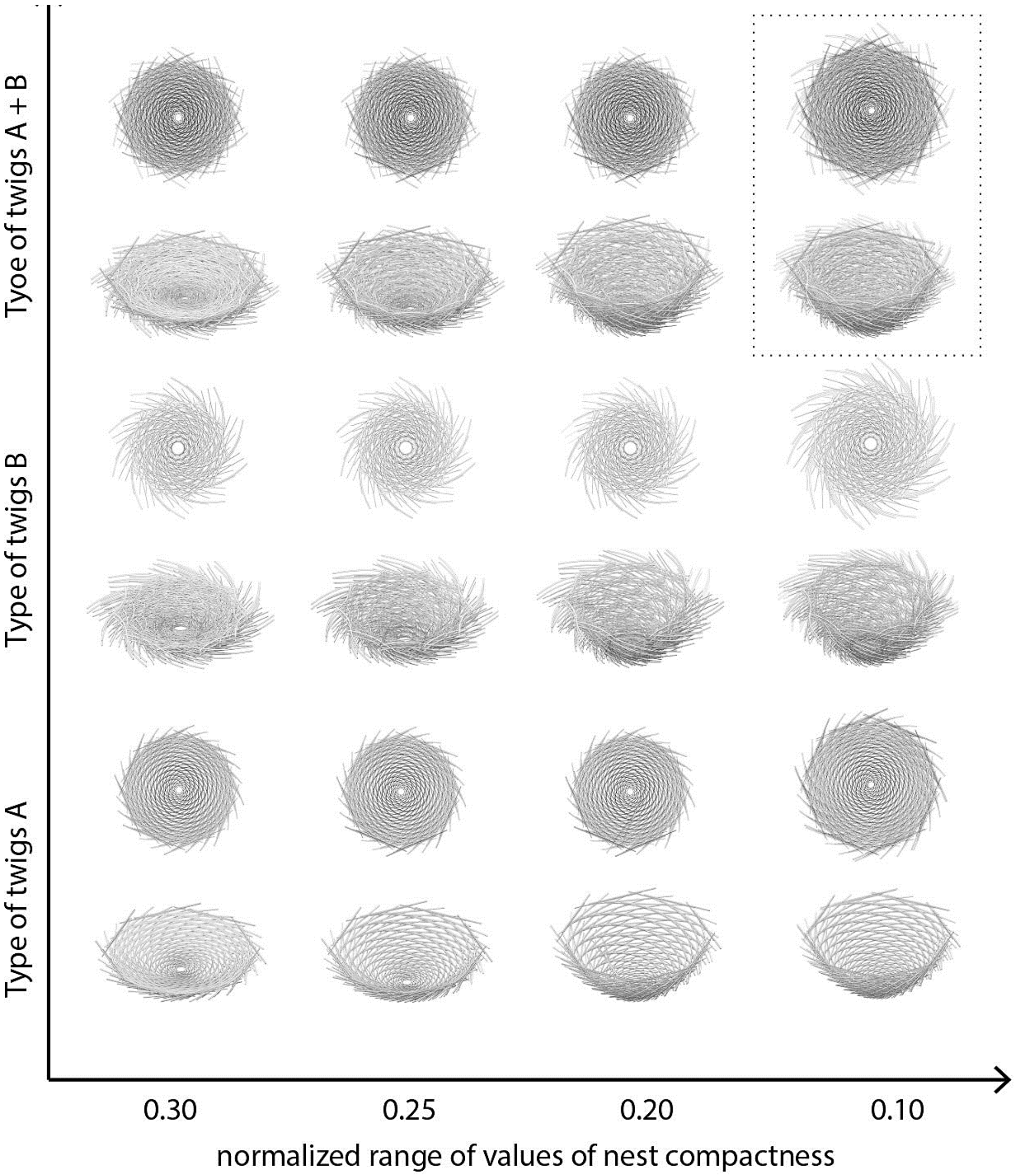

Figure 02: Variations in nest morphology

The highlighted variation from the catalog was chosen for further exploration due to its complexity and similarity to the organic form of the nest. This choice allowed a better understanding of how the Chiffchaff builds its nest.

## 2.2. Analysis techniques: reciprocal frame structure and block stacking problem

After examining multiple variations of the Chiffchaff nest, it was determined that this construction method exhibits similarities to RF structures when contrasted with human-built constructions.

This similarity arises from the RF structure being a system composed of many parts that function as a whole. Moreover, as it is also a self-supporting structure, no central support is required, so all the elements work similarly. This enables the RF units to be designed for reusability and disassembly, streamlining the prefabrication process. Additionally, these structures facilitate the realization of large spans and intricate geometries by virtue of their systemic rather than singular elemental nature.

These units combined create a frame with different possibilities of joints, as long as the frame does not allow movement of the parts. The combination of frames results in a complex volume in which each frame can have a different size or position.

It was further observed that the construction stages of the Chiffchaff nest bore a striking resemblance to the stackable system. The stacking pattern of the Chiffchaff nest demonstrates proportional scaling with its height.

However, this scaling revealed a limitation for a human-sized structure: increased height leads to decreased stability in larger structures, especially making them susceptible to instability around critical tipping points. Consequently, this research team explored an inverse scaling approach. Furthermore, we observed that the outer edges of the stack and their scale offset per layer present a promising possibility for creating walkable steps, suggesting their potential utility in a bridge design. However, while these elements presented viable building blocks for one aspect of the bridge, they needed an essential feature: an overhang. The SP was taken into consideration to address this issue.

This approach involved shifting each layer by a calculated distance, guided by a harmonic stacking equation (HSE). This equation determined the precise shift distance based on factors such as the dimensions of each layer and its position within the overall stack arrangement. The Output-values served as a benchmark against which we compared the efficiency of each iteration. By integrating this stacking principle, we propose a solution that emphasizes the formation of an overhang critical for bridge construction. This method not only leveraged the inherent simplicity of construction but also addressed the need for structural integrity and functionality in the bridge design.

## 2.3. 3D-Modeling and simulation

Initially, we considered a series of a wide array of transformation steps. Several of these were applied to generate a diverse range of geometries, aiming to understand their impact on the stacking behavior and to assess its overall scalability and usability. The GH algorithm (figure 03) initiates by defining a base polygon. Subsequently, it refines it iteratively through a series of ordered operations, guided by parameters such as the dimensions of the base polygon, height and number of stacks/layers (01), scaling per layer (02), a coefficient determining the extent of overhangs in the HSE (03), the amount of extension and tilt of each frame segment (04), degree of rotation for each layer (05) and the number and position of approach sides i.e.. branching (06).

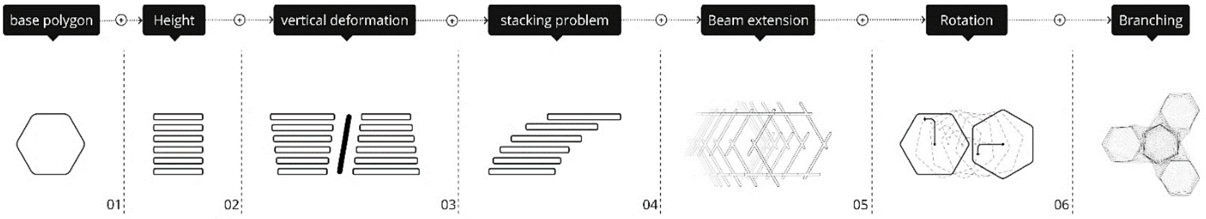

Figure 03: schematic of the GH-parameters and operations order

Rather than adjusting each parameter independently, they are controlled through a graph mapper, dictating the distribution of values across the entire geometry. The graph mapper may involve using a Bezier curve or combining it with the output values of the HSE. The following catalog demonstrates an iterative progression through the main transformation parameters. These iterations help identify correlations between parameters, eliminate flaws resulting from such adjustments, and narrow down the number of resulting geometries, considering factors such as complexity and economic feasibility.

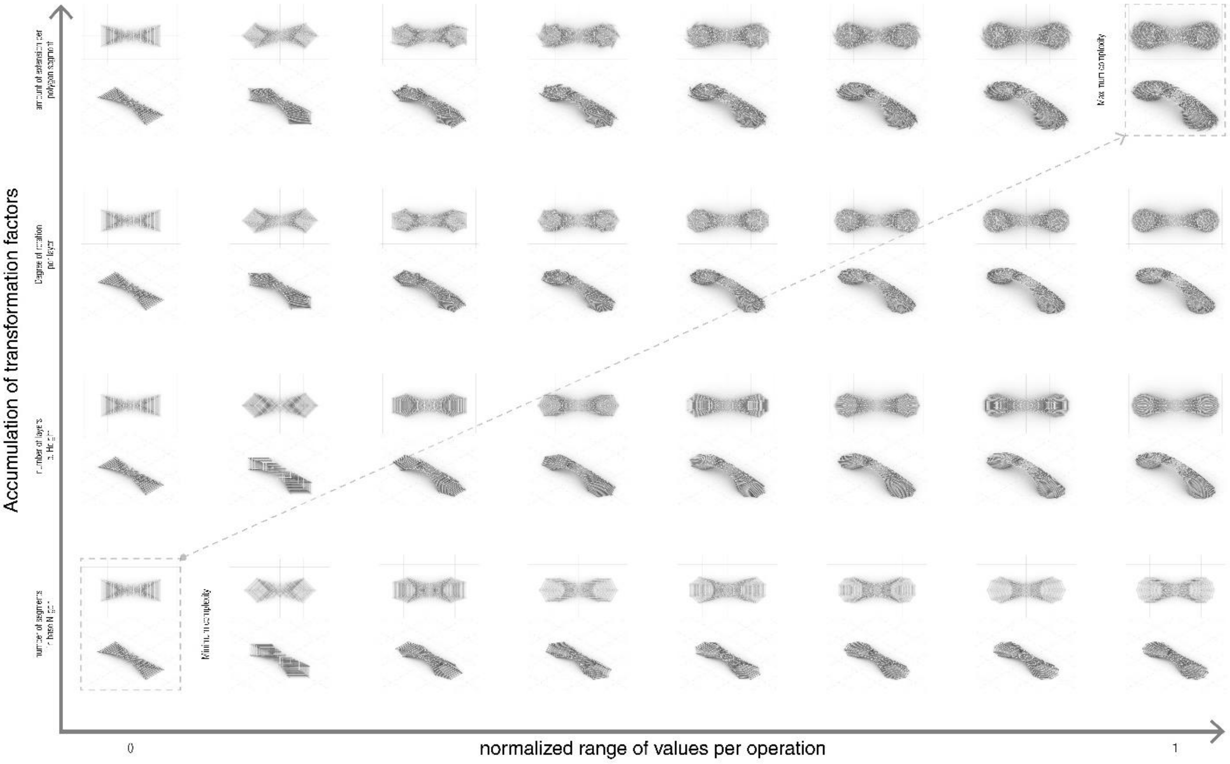

Figure 04: Catalog of the design space through isometric and top views

In the following stage, we prioritize the refinement of geometries utilizing rectangles, pentagons, and hexagons due to their simplicity while ensuring a series of intersections between the segments of vertically adjacent frames.

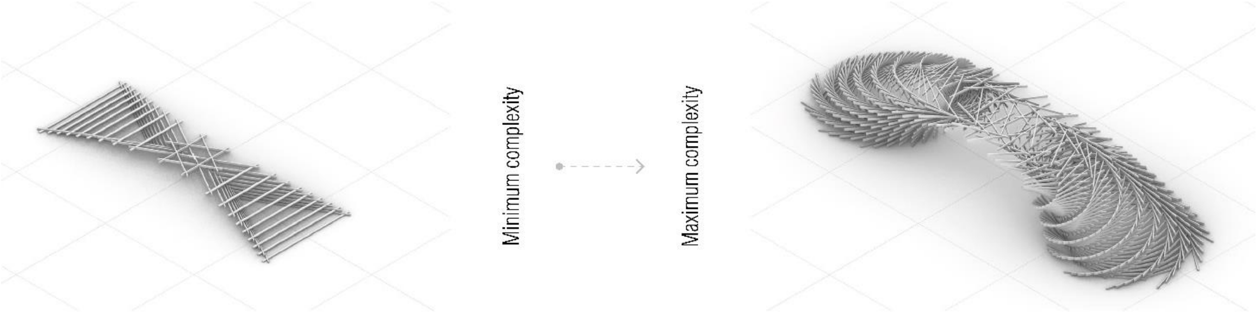

Figure 05: complexity extremes of the generated catalog, isometric Views

After comprehending the geometry's behavior across all factors, we eliminated, simplified, or correlated specific operations. For example, the base polygon's dimensions depend on the number of layers' height to guarantee more coherent outcomes.

The geometry with a rectangular base was chosen as the most suitable and further detailed because it has fewer segments per layer, leading to faster construction. Additionally, its more comprehensive steps allow for a more spacious pathway for use as steps or staircases, and its joints are easier to fabricate due to the intersection angles being closer to 90 degrees.

In the next phase, we addressed the irregularities in step depths resulting from the raw stacking behavior by offsetting the edges that define the steps. However, this action shifted the center of mass of each layer to an unfavorable position, posing a risk to the structure's stability. To address this issue, we reassigned specific transformation factors to respond to these irregularities, such as adjusting the tilt of the longitudinal frame segments and their extension. Through these adjustments, we realigned the center of mass of each layer accordingly.

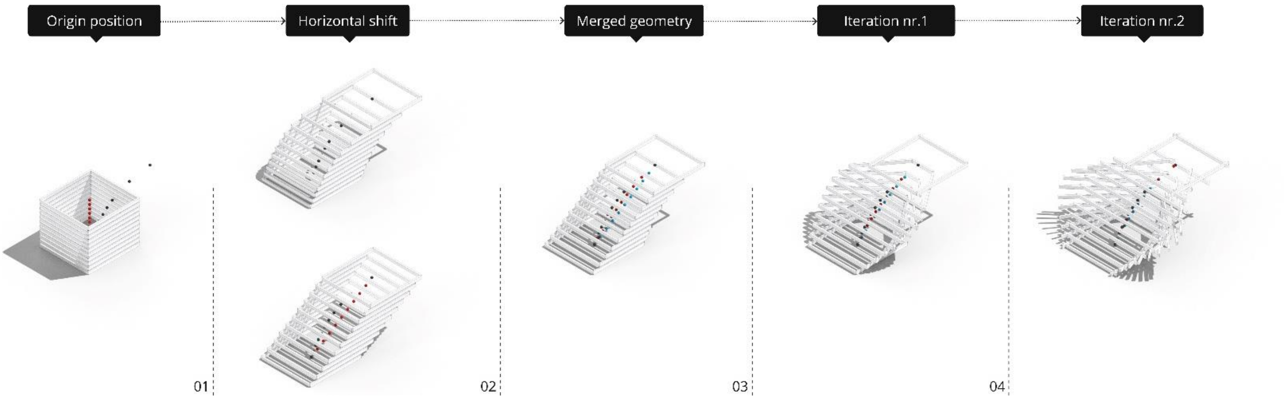

Figure 05: Isometric view of the morphing stages

## 3. Results and discussion

### 3.1. Interpretation of the Chiffchaff's Nest Structure using reciprocal frames

The Chiffchaff constructs its nest on or near the ground, typically in concealed locations within brambles, nettles, or dense low vegetation. The nest, which is dome-shaped with a side entrance, is crafted from coarse plant materials such as dead leaves, stems, and grass. Before adding a feather lining, delicate materials are utilized on the interior. The Chiffchaff carefully selects twigs and elements based on specific size criteria. A typical nest measures 12.5 cm in height and 11 cm in width.

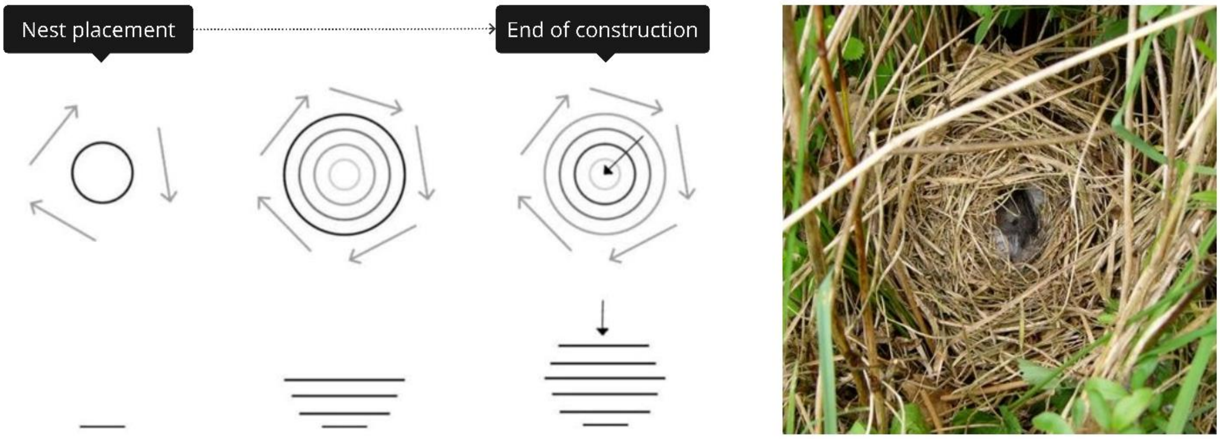

Figure 06: Left: Nest building stages, right: Photo of a Chiffchaff's nest [4]

On the one hand, unlike human-made structures, Chiffchaffs cannot build their nests with standardized pieces; instead, the twigs vary in shape, sometimes straight and other times more curved. Similar to traditional RF structures, the ends of each element extend beyond the joints. However, unlike conventional RF structures, the Chiffchaff's nest incorporates curved or imperfect twigs, enhancing their grip with adjacent components, even if they are not necessarily from the same frame. On the other hand, the weight that these structures (the bird) receive is borne by the nest's interior and is not applied to the branches that make up its structure; these elements primarily serve for insulation and protection.

### 3.2. Stacking problem and maximum overhangs

While the HSE establishes a theoretical maximum overhang, translating this value into a practical, constructive reality presents challenges. Nevertheless, it serves as a valuable reference point guiding the modeling approach.

In addition to the dimensions of the base Polygon, a coefficient (K) plays a crucial role in the equation. The higher K, the smaller the horizontal shift gets, and the less overhang we produce, and vice versa.

[Horizontal shift = Length of linear Element / (K * Position of the element in the vertical arrangement)]

As a rule, to achieve the theoretically maximum attainable overhang of identical stackable linear elements, K is set at 2.0. However, this theoretical maximum is not practical, and with the operations we considered, we cannot reach it. It was adjusted to achieve a more pragmatic "buildable" overhang. We further explored the value of K in the range of 1.0 to 3.0 to analyze its impact. Subsequently, it was set within the narrower range of 2.1 to 2.5 to achieve a more compact and stable structure.

Another aspect worth noting is that the HSE, in its simplest form, considers each layer as a linear element with uniform volume. In contrast, each layer of the examined structure resembles a contour with minimal weight at its center, potentially offering additional advantages in weight distribution.

### 3.3. Insights from 3D modeling

In the initial stages, it was helpful to introduce as many factors as possible to explore the potential of such a structure with little prior experience. With each reduction and exclusion of an operation, a better grasp of the structure's behavior was developed.

In this manner, an understanding was developed of how the following aspects influence the stability of a structure: the position of the center of gravity within each layer, its position concerning the adjacent layers, the distance between them, and the tipping point in the direction of the overhang, and lastly the overall distribution of the centers of gravity and the tipping points in the general geometry.

Various tools, including Karamba [5] as a Finite element analysis (FEA) solver, were investigated to extract an analysis of the proposed composition of RF. However, delving into these tools proved challenging due to the complexity of establishing a hierarchical order for the intersecting frame segments. With frames morphing cumulatively and iteratively, higher input values were assigned to each parameter, resulting in more complex geometries and a rapid intersectional surge. This made the identification of necessary joints increasingly tricky.

For these reasons, this method appeared more time-consuming than efficient. Therefore, orienting each iteration around fixed values and constructing the GH-Script around them yielded quicker results. In this regard, the HSE and its integration or correlation with other parameters played a crucial role. This simplified analytical measure improved the reaction time to readjust, enhance, or filter various design aspects significantly.

### 3.4. Translation to an architectural scale application

One of the most significant benefits of designing such a structure within a parametric workflow, where each element follows a systematic logic in its form and composition, is the ability to derive actionable information. From the Grasshopper script, data can be extracted to generate manuals containing detailed, to-scale drawings of each frame. Alternatively, 3D geometries can also be extracted to facilitate seamless integration into more precise file-to-factory manufacturing methods, such as CNC milling. Furthermore, the sequence to compose the intended structure can be extracted to accelerate its assembly process.

During the prefabrication phase, orientation markers and other identifiers could be integrated into the milling process to facilitate a smoother transition from prefabrication to construction. In cases of manual production, such markers could be incorporated into the documentation.

### 3.5. Proposal for a self-supported cantilever construction system

The bridge's structure is conceived as two self-supporting and structurally stable halves, each constructed separately and finally joined with a prefabricated frame resembling a keystone in vault construction. The frames comprise two transversal and two longitudinal beam segments, with the first two being vertically shifted by half of the step height.

The first layer/frame is laid and connected to foundations that could be realized as stone or concrete. The frame needs to be appropriately secured and fixed to the foundation, considering the later emerging loads from using the bridge and as a precaution against any additional loads that might result from the assembly phase.

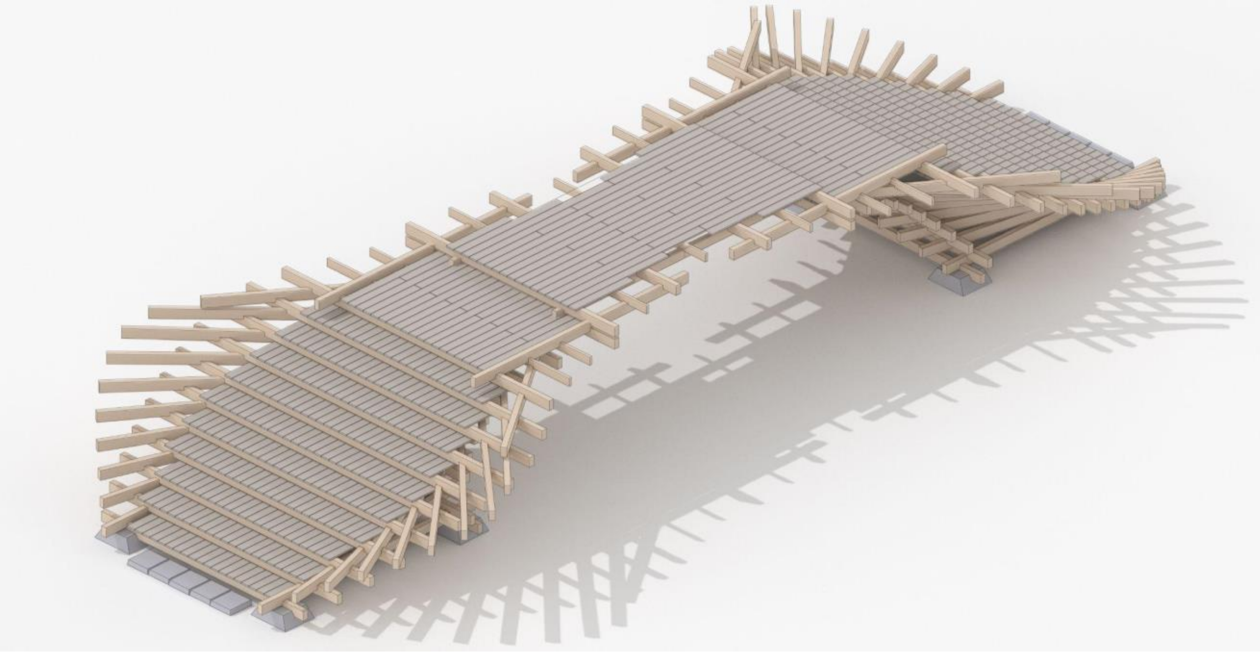

Figure 07: Assembled bridge, isometric view

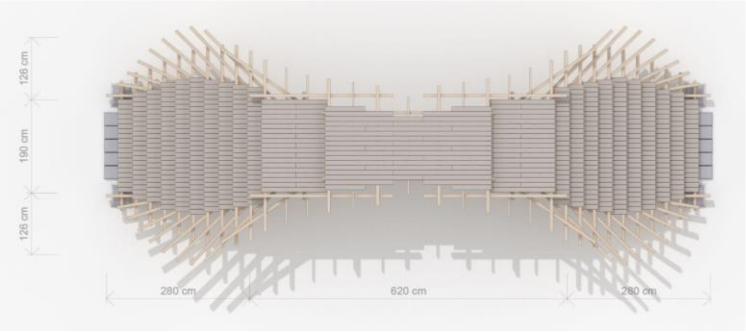

Figure 08: Final dimensions
of the proposed Bridge, Top view

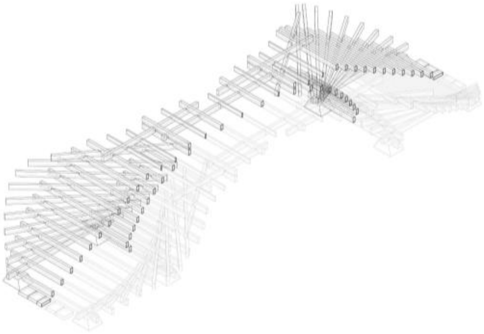

Figure 09: The skeletal structure
, isometric section

Each half of the bridge structure is assembled by stacking frames on each other, interlocking through prefabricated niches that prevent horizontal movements in the horizontal plane. The bond between them is further reinforced by Screws joining the two adjacent frames. Immediately after joining two frames, the steps of that level could be directly assembled, thereby increasing the structure's weight at the furthest section from the tipping point and consequently enhancing its stability.

## 3.6 Constructive Details and Material choices

The entire structure is built using laminated construction timber (6 cm x 12 cm). Each frame consists of four beams, with the joints between each pair of beams created by machining a 2.5 cm deep niche on both sides to ensure a secure interlock between layers

Figure 10: machining of the Timber beams on a 3-Axis CNC

The joints were then secured by driving a screw vertically through the center of each joint. By achieving a tight fit between the niches in the beams, the joints are fixed against translational movement and are somewhat resistant to rotational movement, particularly in the Y-plane (i.e., the horizontal plane).

Figure 11: close-up Detail of the joint and the 1:1 Model of a bridge section of the Timber beams on a 3-Axis CNC

## 4. Conclusion: submission of contributions

Through an evolutionary process, many living creatures, particularly birds in this case study, have developed and refined construction methods tailored to their specific needs. With many species encountering varying materials, environments, stimuli, and requirements, many construction methods have emerged, each consisting of multiple simplified steps. This choreography in nature offers valuable insights that can be analyzed and applied across numerous areas of human construction. Whether in designing structures, material selection, or problem-solving methodologies, the lessons learned from nature's ingenuity can inspire innovative solutions in human endeavors.

In this study, we aimed to integrate two phenomena, the nest-like patterns of RF Structures and harmonic stacking, and develop the most physically feasible architectural application, offering insights into additional opportunities. Some involve exploring alternative biomimetic structures, refining weaving-like patterns, and adapting them to a systematic or adaptive distribution of linear elements, among other possibilities for manipulating the relationship between these building elements. Timber beams and similar building materials emerged as ideal candidates for this construction system due to their ability to compose discrete elements with short dimensions. The material selection facilitates ease of replicability, disassembly, and reassembly. Making it a cost-effective solution for temporary structures.

Envisioning the potential of this application requires acknowledging the ever-present processing power available today. Such a system could simplify and elevate its inputs to a more user-friendly level accessible to individuals, empowering them to address various needs. Furthermore, exploring additional use cases beyond bridges opens possibilities for incorporating architectural elements such as partial domes, loggias, and more, thereby expanding its scope.

As digital technology becomes more accessible and affordable, it has the potential to make such algorithms, as in this paper, more efficient. This could help communities without access to professional planners, and engineers use these tools for their projects, like building homes or infrastructure.

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