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Defining geometries for reusable plate systems

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Abstract

In the event sector, structures are often left behind after use, ready to be thrown away. This leads to increased waste and CO2 emissions. However, if 75% of structures were reusable, waste production would be up to 3.5 times lower. By designing these temporary structures to be lightweight, modular and reconfigurable, they are more efficient for short-term use and reuse. However, current solutions are difficult to assemble or lack variation to achieve different configurations. When multiple configurations are possible, they usually consist only of beams and do not include walls or provide coverage. Therefore, this research will focus on investigating a lightweight plate-based building system for temporary, reconfigurable and structural applications.

A first step in this process is creating an overview of geometries that are composed of a small range of distinct components. Later, this geometrical system can be translated into a resource efficient plate component and an innovative connection system that allows for the predefined configurations. The geometrical system is based on existing solids that are combined with other mathematical shapes to enlarge the amount of configurations and the range of modularity within each geometry. To go from the theoretical system to the eventual physical prototype, several case studies are analyzed in regards to potential plate components and connection systems. Further research will focus on defining a connection system that allows to obtain a specific range of configurations.

Keywords: reuse, modularity, morphology, connection system

1. Introduction

To use our building materials more efficiently it is important to optimize their reuse. The reuse of these materials embedded in building blocks can be maximized by allowing the blocks to be used in a variety of different structures. As temporary structures change users even more frequently, their building blocks should be designed to allow a quick assembly and disassembly.

To achieve this reusable building system for temporary applications, the structure can be optimized on three levels, namely the geometry, the plate system and the connection system. The focus of this paper is the optimization of the geometry.

By limiting the amount of different modules needed for the structure, the assembly requires a less extensive building plan and the time needed for naming all modules can be saved. Modularity often helps to simplify this process, since the used elements are standardized. This standardization even allows a flexibility to create several designs with the same 'module'. Thus, through modularity only a small range of distinct components are needed to create a variety of different configurations. The ReciPlyDome for instance, only requires one to four types of beams to create six different structures [1]. Another example is the '1-to-3' multipurpose kits of parts pavilion that uses six to twelve bars and one clever spherical joint to obtain three different shapes [2]. Though these structures offer the flexibility to create multiple configurations, they are only made of beams and thus don't yet offer any coverage.

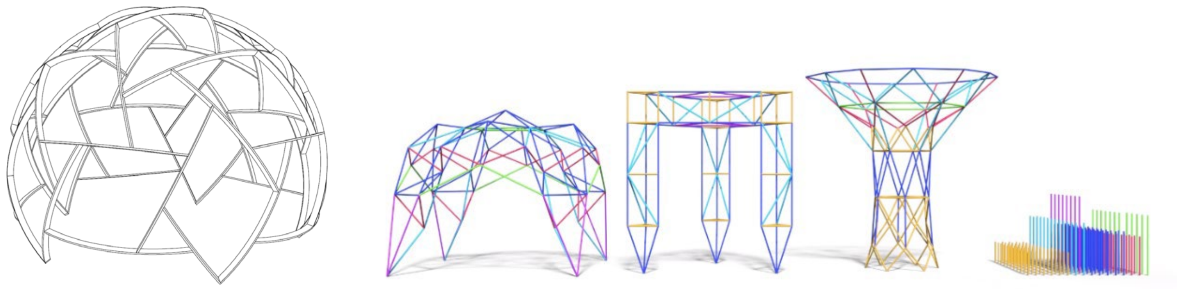


Figure 1: Left: The ReciPlyDome [Leemans et al.,2023]. Right: the 1-to-3 multipurpose kits of parts pavilion [Brütting, et al. 2021].

A more suitable option would be to use plates, combining both the structural aspect and the coverage into one element. However, this often complicates the connection system and reduces the flexibility to change its shape. This can be seen in the differentiated wood lattice shell [3], as the varying shape has to come from within the module itself. Additionally, the extra weight of the plates often requires the use of scaffolding during the assembly, as shown with the modular timber structure [4], which diminishes the efforts of modularity to create more resource-efficient structures.

In freeform plate structures, such as the Pentaura [5] and Folding Flax Pavilion [6], usually a top-down approach is chosen whereby the shape of the structure is defined first, after which it is divided into the various plates. In this research the opposite approach is taken. To create a reusable building system we will start by searching for a small range of distinct components, which later can be used to create various configurations.

To investigate how this reusable building system can be created with lightweight modular plate components, existing solids were researched. Some of these solids, such as the Platonic solids, the Archimedean solids, the Catalan solids and the Johnson solids, already have a certain degree of modularity. Through combining several aspects of these solids, the range of modularity can be increased and the amount of variations can be expanded. To verify the application potential of these new shapes, three case studies are investigated more thoroughly through small-scale models and prototypes.

Figure 2: Top left: Differentiated wood lattice shell [Huang and Park 2009]. Top right: Modular timber structure [Nabei and Weinand 2012]. Bottom left: Pentaura [MPDA, 2023]. Bottom right: Folding Flax Pavilion [IAAC, 2017]

2. Expanding the Archimedean Solids

To achieve a large amount of configurations, existing solids with a certain degree of modularity are analyzed. All five platonic solids consist each of only one type of equilateral polygon, ranging from triangles to pentagons [7]. Though their small range of required modules is ideal, the small amount of modules results in small domes if a respectable size for the modules is applied, which makes them not efficient to use for structural geometries.

The thirteen Archimedean solids consist each of two to three types of equilateral polygons, ranging from triangles to decagons. This means that all thirteen of the Archimedean solids can be formed with six types of plate geometries [8]. Although this is already relatively modular, the solids can be discretized even more by applying several levels and variations of augmentations or cupolas.

Augmentations and cupolas are derived from the Johnson solids, which is a collection of 92 polyhedra [9]. In the case of augmentations, the faces of the polygons are replaced by pyramids with a base equal to the polygon (Figure 3, left) [10]. Cupolas are created by a polygon with *n* sides and a polygon with *2n* sides that are separated through *n* triangles and *n* squares (Figure 3, right) [11]. By replacing the larger modules of the Archimedean solids, such as hexagons, octagons and decagons with these cupolas, the amount of different modules is reduced to three. To discretize the solids even further, triangles squares and pentagons can be replaced by their augmentations. However, for the triangles and squares especially, this will make the structures less efficient as the base plate is replaced by three or four plates that have similar sizes to the base plate. Therefore in this research augmentations are only applied on pentagons.

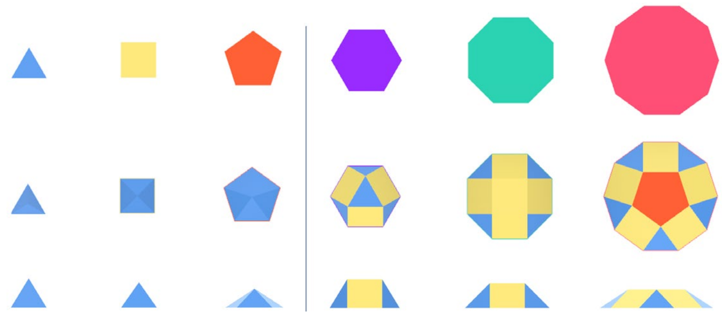


Figure 3: Left: Top view and side view of an augmentation for an equilateral triangle, square and pentagon. Right: Top view and side view of cupolas with hexagon, octagon and decagon as a base.

The Archimedean solids mentioned in this paper, which are altered through augmentations or the addition of cupolas are grouped under the name 'Augmented Archimedean solids' (Figure 4). The names for the individual solids are determined by the following rules.

1. Replacement of the largest polygon by an augmentation or cupola
   = 'augmented' + 'name of altered Archimedean solid'
2. Additional replacements of second largest polygon by an augmentation or cupola
   = 'doubly' + 'augmented' + 'name of altered Archimedean solid'
3. Orientation of the augmentation or cupola : aligned / not aligned

A visualization of the naming conventions can be found in Table 1.

Lastly, the thirteen Catalan solids consist each of only one type of polygon, however none of these polygons can be used for more than one type of Catalan solid [12]. In future research it can be investigated if modular plates with a certain flexibility can be used for more than one type of Catalan solid.

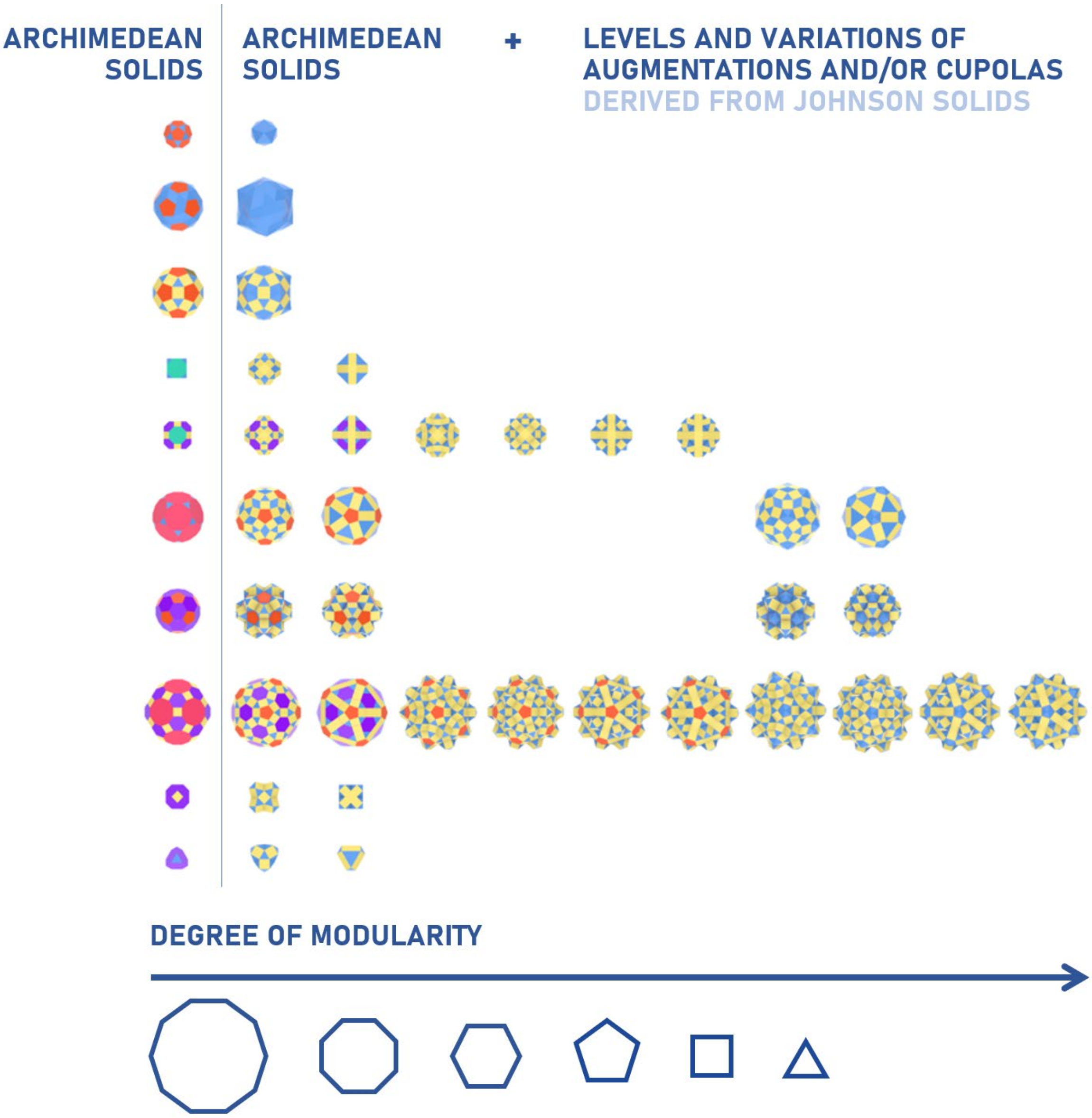
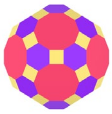
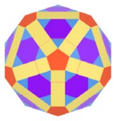
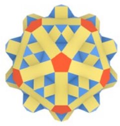
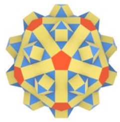
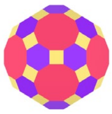
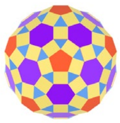
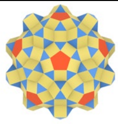
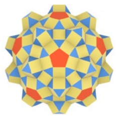


Figure 4: Expansion of nine out of thirteen Archimedean solids through adding levels and variations of augmentations and/or cupolas.

Table 1: Naming conventions for the Augmented Archimedean solids.

Orientation	Archimedean solid	First alteration	Second alteration
Aligned (A)	 Truncated Icosidodecahedron	 Augmented Truncated Icosidodecahedron (A)	 Doubly Augmented Truncated Icosidodecahedron (Doubly A)
			 Doubly Augmented Truncated Icosidodecahedron (A – NA)
Non-aligned (NA)	 Truncated Icosidodecahedron	 Augmented Truncated Icosidodecahedron (NA)	 Doubly Augmented Truncated Icosidodecahedron (Doubly NA)
			 Doubly Augmented Truncated Icosidodecahedron (NA – A)

2.1. Linear expansion

When expanding the Archimedean solids through discretization, the resulting structures are still domes. To create a more versatile list of configurations, a linear expansion is explored. A fully closed linear expansion is only possible in cases where base modules are replaced by cupolas or where other folding lines are present. When one cupola or a fragment adjacent to a folding line is removed from two solids they can be joined to form an elongated shape.

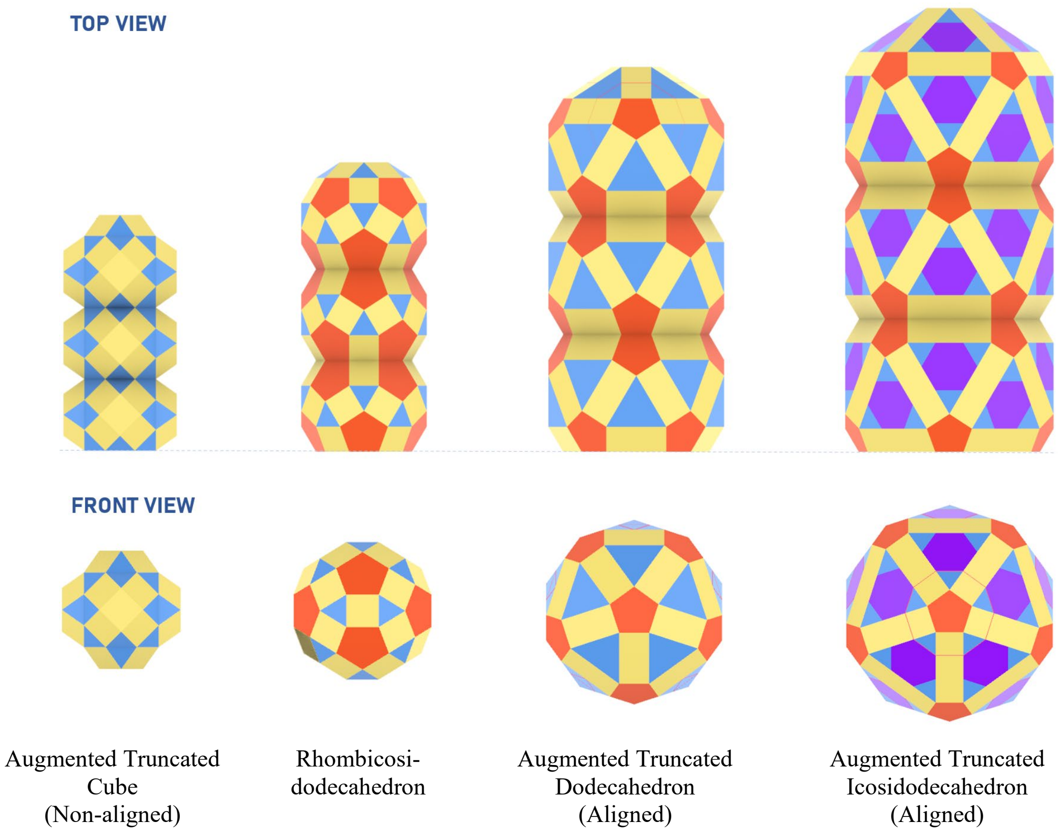


Figure 5: Linear expansion of several Archimedean and Augmented Archimedean solids.

2.2. Freeform expansion

When not starting from the researched solids, other more freeform shapes can be found using the same range of components. By creating the structure from the components instead of the geometry, high component uniformity can be achieved in freeform shapes. This bottom up approach results in a cantilevering structure containing 30 triangles, 12 squares and 3 pentagons. Though only being one example of a freeform structure, this small range of components looks promising to expand the amount of configurations in the future from domes to a variety of different shapes.

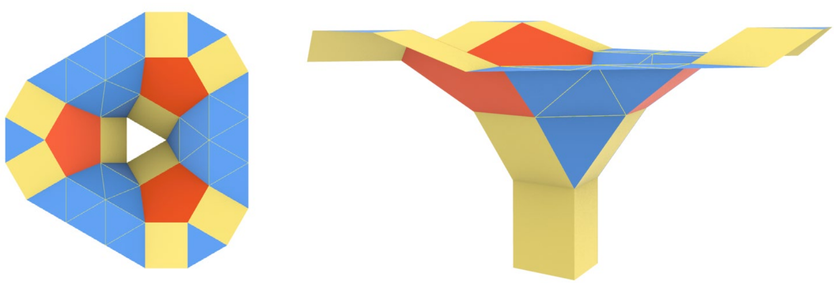


Figure 6: The freeform 'umbrella' shape. Left: top view, Right: perspective view. From the master thesis of Rebecca Van Daalen.

3. Prototype exploration

3.1 Geometrical models

The proposed geometries were verified by means of small-scale models. Specifically, the Rhombicosidodecahedron, the Augmented Truncated Dodecahedron (NA), the Doubly Augmented Truncated Icosidodecahedron (Doubly NA) are investigated as they have a good variation in scale and complexity of the structure.

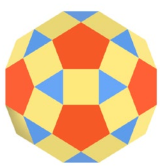
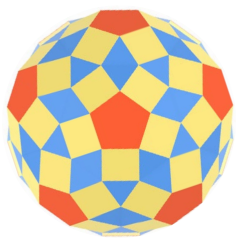
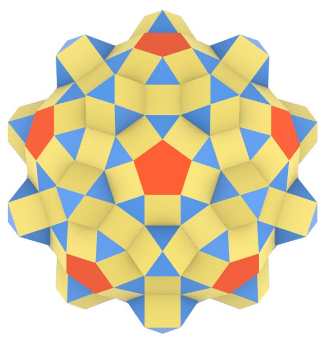
The three abovementioned structures are tested by making small-scale models. Due to the scale of the models, the plates will be connected with tape. The tape serves as a 'textile hinge' so the stability of the geometry itself can be tested with the models. Additionally, the flexibility of the tape also facilitates working with the various angles that are present in the different structures. In a bigger prototype the tape will be replaced with hinges.

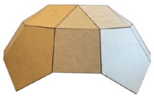
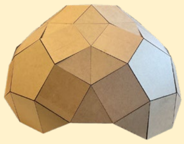
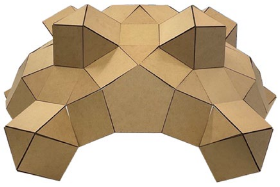
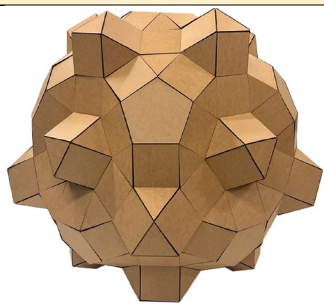
As the domes will rarely be used in their fully completed shape, it is investigated if their separate layers also provide stable structures. the domes are Therefore built up layer by layer. This also gives a good insight in the assembly process, which is crucial for the reusability of the system. In this case the domes were built up in an upside-down manner, and then flipped over to verify the stability of each layer. Though this assembly method is efficient on this scale, it should be adapted when working on a bigger scale. When working on a full scale structure, inverting the structure will evidently not be feasible. Therefore, a lift will be place in the middle of the structure onto which the top plate, in these three case a pentagon, will be attached. Thereafter the structure will again be assembled layer per layer, while raising the structure upwards with the lift after finishing each layer. A similar method was used successfully for the assembly of the ReciPlyDome [13].

In Table 2 the several layers of the three solids are displayed from L1 to L6. The unstable layers are indicated in yellow. In case of the Augmented Truncated Dodecahedron (NA) the fourth layer is unstable as the bases are located on a folding line. This folding line will eventually be stabilized by the completion of the cupolas that are visible in layer 5. The Doubly Augmented Truncated Icosidodecahedron (Doubly NA) becomes unstable from layer 6 onwards. However, in this case it was not clear if the instability was due to the shape of the structure or due to the insufficient strength of the tape.

By creating these small-scale models, the structural stability of most layers of the explored domes can be validated. Apart from testing the overall geometrical stability, it also helped verifying the top-to-bottom assembly method which can be applied in full-scale structures. The next step is to test fragments of these domes on a larger scale with more secure connection system such as hinges.

Table 2: Exploration of the Rhombicosidodecahedron, the Augmented Truncated Dodecahedron (NA) and the Doubly Augmented Truncated Icosidodecahedron (Doubly NA).

	Rhombicosidodecahedron	**Augmented Truncated Dodecahedron (NA)**	**Doubly Augmented Truncated Icosidodecahedron (Doubly NA)**
Shape			

	20	80	140
	30	60	150
	12	12	12
Size Full Dome	42.36 cm	60.33 cm	79.34 cm
L1			
L2			
L3			
L4			
L5			
L6			instable
Full Dome			

3.2 Prototype analysis

To verify further the feasibility of this geometrical system, one case study is explored through small scale prototyping, taking linear hinge connections into account. The case study chosen is the rhombicosidodecahedron of which the plates are joined by interlinking cupolas with a decagonal base. Therefore a prototype of a single cupola and of two joined cupolas is tested. On this scale hinges are used to connect the plates and allow for all necessary connection angles.

In these prototypes the folding lines especially stood out, as visualized in yellow in Figure 7 and Figure 8. The structure is stable when completing a cupola, as can be seen in Figure 7. However when joining two cupolas, two new folding lines are created (Figure 8). To stabilize the structure, a full layer as shown in Table 2 should be completed.

Additionally, the use of hinges showed that the tolerances should not be too big, as otherwise gaps between the plates are created. While not having a big effect on one cupola, it becomes especially visible in Figure 8 where two cupolas are combined. These prototypes showed that both the sequence of construction as the detailing of the connection systems are crucial elements for the stability of the structure. In future research the connection system will be further explored.

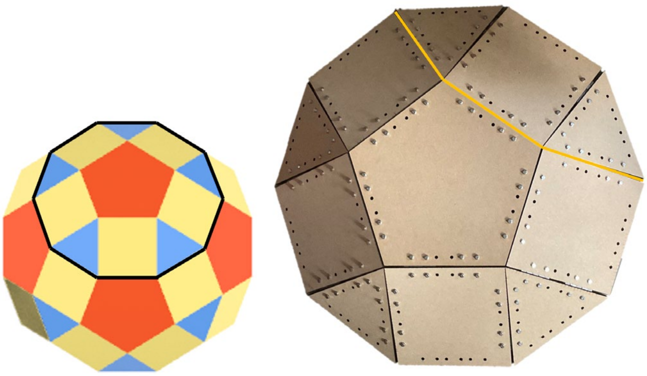


Figure 7: Fragment of the Rhombicosidodecahedron: a hinged cupola. One of the folding lines is indicated in yellow.

Figure 8: Fragment of the Rhombicosidodecahedron: two joined hinged cupolas. Top: Top view, Bottom: side view. One of the folding lines is indicated in yellow.

4. Conclusion

By expanding the Archimedean solids with other mathematical concepts such as augmentations and cupolas, a new overview of configurations is created. To expand this collection even more, some of the solids are combined in a linear manner to form more elongated shapes. Additionally, when starting from the plate components itself, freeform shapes with high component uniformity are created.

Through creating small-scale models and prototypes of these domes, the geometries of these domes were proven to be stable on most layers. However, attention must be paid to the folding lines, as incomplete layers could result in instabilities. Additionally, testing the structure layer-by-layer helped to verify the top-to-bottom assembly method.

Future research lies in creating prototypes on a larger scale and conducting a numerical analysis on a selection of these shapes. Apart from the geometry, there will be a focus on creating an adjustable connection system that can be used for all configurations. Additionally, the plate system will be further explored to find a good balance between stiffness and material efficiency.

Acknowledgements

The umbrella shape in section 2.2 was taken from the master thesis of Rebecca Van Daalen (VUB, 2024).

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