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GENERATIVE DESIGN BASED ON SPONGE SPICULES' FORMS

PENGYU ZHANG[1], WEIGUO XU[2], WEIXIN HUANG[3], YUFENG ZHU[4], RUI DAI[5] and DAN LUO[6]
[1,2,3,4,5,6]*School of Architecture, Tsinghua University, China*
[1]*zhangpengyu9921@163.com* [2]*xwg@tsinghua.edu.cn*
[3]*huangwx@mail.tsinghua.edu.cn* [4,5]*{1912351430|835399659}@qq.com* [6]*luo_dana@126.com*

Abstract. A bio-based generative design approach is proposed with an application based upon sponge spicules. The approach aims to generate new valid architectural form finding methodology through the imitation of biological forms. The process includes five stages: Prototype Study, Imitation, Creation, Application and Fabrication. In the development of the approach, sponge spicules' forms, which are uniquely varied in the nature, are digitally imitated. Based on the imitation, a variety of formal outcomes are created. Some are suitable for architectural design and can be properly fabricated. Both the approach and the application on sponge spicules may contribute to the bio-based creative design exploration.

Keywords. Generative Design; Design Approach; Biomimicry; Sponge Spicules.

1. Introduction

The paper presents a bio-based generative design approach with an application based on sponge spicules. As the result of natural evolution, a variety of biological forms are highly developed with effective structural performance, material composition and function organization. Many of the forms have inspired sustainable design and the design of new material, product and structure in the past (Trotta 2011; Liu & Jiang 2011; Baerlecken et al. 2012; Peters 2011). However, the biological language and analogies in some researches have diminished humanity and human achievement in design (Kaplinsky 2006). Furthermore, most of these researches focus more on the imitation of natural forms rather than on their growth mechanisms; and the role of designers has been ignored.

In the presented approach, the biological and architectural knowledge are combined. The application of the approach is not only to get the well-imitated forms, but also to create more forms based on similar mechanisms and apply principles extracted from mechanisms to the architectural problem solving. What's more, the designer plays a significant role in bio-based generative design by this approach.

In this paper, sponge spicules' forms are taken as an example to describe the new approach to bio-based generative design. Biological forms, similar to sponge spicules' forms, such as bone, phyllotaxis, cellular structures of wood and so on, have been well explored, showing a wonderful perspective of bio-inspired architectural form finding (Nsugbe & Williams 2001; Hensel 2006; Menges 2012). While sponge spicules' application in the field of architecture is still under-explored.

Sponge spicules have the potential to be developed into architectural forms. Sponge has been used as the prototype of minimal surface and parametric modeling (Vamvakidis 2007; Weston 2013); and its bone tissue has attracted architects by its highly differentiated structure (Weinstock 2006). Spicule has inspired material design because of its contribution to the structural integrity and strength of sponge (Aluma et al. 2011); and it has the potential to form mesh or honeycomb structure when assembled (Weinstock 2006).

Sponge spicules' forms are well-imitated and a variety of forms based on the similar mechanism are created with the following new approach. Both the approach and the process of generative design based on sponge spicules' forms are introduced as follows.

2. Approach

The approach to bio-based generative design is based on biomimicry to create new valid architectural forms. It has two main goals. One is to develop the attractive and efficient biological forms into architectural forms, which is based on the imitation of biological forms and the creation for new different forms. The other is to apply principles extracted from growth mechanisms of biological forms to the architectural problem solving. The foundation of the second goal is the similarity of biological adaptation and architectural optimization. In the nature, biological form never stops evolving to face the changes and challenges in the habitat and becomes more and more adaptable. In design, the designer modifies plans over and over again to find better solutions of existing problems and make the buildings fit the surroundings better. To this sense, the growth mechanism of biological forms may inspire the designers to find a new way for problem solving.

Five stages are included in the process: Prototype Study, Imitation, Creation, Application, and Fabrication (figure 1). Different from the previous biomimetic design, the designer plays an important role in the process.

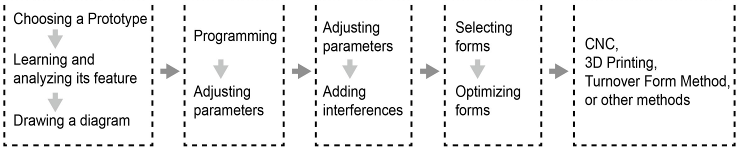

Figure 1. Five stages in the approach.

Firstly, Prototype Study is the basic stage and based on a primary investigation into the prototype. The prototype is butterfly, conch, coral, or other creatures and morpha in the nature. By analyzing its morphology and the growth mechanism, the prototype is described with a diagram.

Secondly, Imitation is based on the prototype diagram to make accurate imitation of the biological form. By programming with digital software, such as Processing, Python or Grasshopper, the prototype is accurately imitated when setting proper parameters.

Thirdly, Creation aims to generate new forms based on the prototype. On the basis of the program in previous stage, multiple novel forms different from the prototype are created by adjusting parameters or adding interferences. And the forms still follow the similar growth mechanism as the prototype and also resemble some of its features. Furthermore, although these forms are created based on biomimicry, the quality of the created forms depends on the creative and design ability, and aesthetic judgment of the designer.

The fourth stage is Application, and its main task is to select and optimize the forms for architectural use and further fabrication. Although multiple forms are created in previous stage, only few of them are selected. After selection, parameters and interferences in the program may still need to be changed to optimize the forms.

The final stage is Fabrication. Many different methods are used for the fabrication of different forms, such as CNC, 3D Printing, Turnover Form and so on. The main task is to choose a proper method and make a model.

Many of various biological forms in the nature can be developed for the architectural application by the approach introduced above. With the five stages, the approach can be easily adopted for form finding and generative design.

3. Process

In this part, the application of the approach based on sponge spicules' forms is introduced with five stages.

3.1. PROTOTYPE STUDY

Spicule can be found in most sponges (figure 2). It is of high diversity on account of the taxonomic richness of sponges (Butler 1961). And a morphologic classification has been made to identify and describe different sponge spicules based on "composition and general architecture of the individual spicules", "the form of the sponge" and the manner to "construct the skeletal structure" (Butler 1961). Their functions vary from providing mechanical rigidity to deterring predators (Aizenberg et al. 2004). And the functions imply that they may have the valid structure to serve as architectural forms. Also, their growth mechanism is interesting. Spicules are generally elongated with silica to the sclerocyte (Imsiecke et al. 1995). Once a spicule reaches a certain length, it protrudes from the sclerocyte cell body, and occasionally, sclerocytes generate a second spicule while the first one is still in progress (Imsiecke et al. 1995).

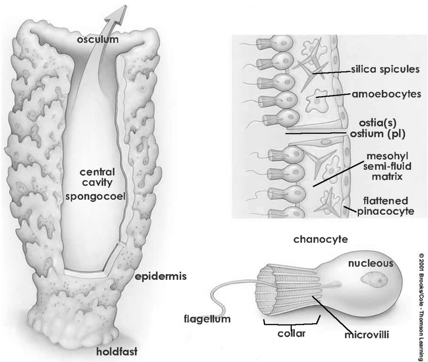

Figure 2. Spicules in a Sponge(extracted from Brooks/Coles-Thomson Learning 2001).

3.1.1. Feature Analysis

There are many different sponge spicules' forms in the nature (figure 3). And three kernel features are summarized as follows.

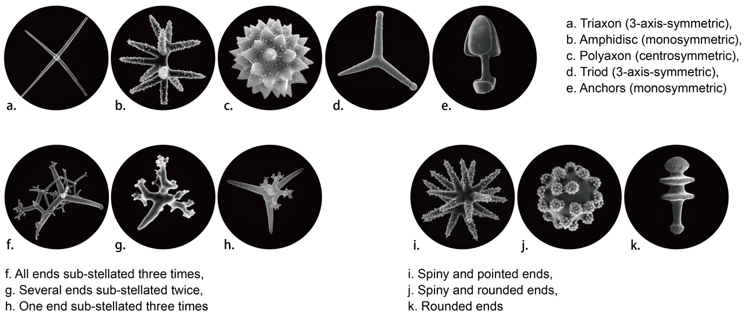

Figure 3. Various Spicules in the nature. a - from Van Soest (2009); b, i - from Cardenas & Rapp (2012); c-g, j - from Van Soest et al. (2012); h - from Muricy et al. (1998); k - from Lehnert et al. (2006).

The first one is the symmetrical axis. The number of axes in spicules varies from one to four, and even more, depending on species; and categorized by the number of axes, spicules are described as Monaxon, Triaxon, Tetraxon, Polyaxon, and so on (Andri et al. 2001). The second feature is stellated. For example, central symmetrical spicules are all stellated forms, while some spicules contain multiple sub-stellar with smaller branches expanding in one, several or all directions (Van Soest et al. 2012). Last of all, there are various mutations to spicules' ends. The ends are pointed, rounded, spiny, or very small sub-stellated branches (Van Soest et al. 2012).

Furthermore, some spicules with more than one axis, have axes bearing a similar ray, while others' axes lying in different planes (Andri et al. 2001). And some take irregular forms, while others form structures with an I, Y or X shape (Rigby & Boyd 2004; Bingli et al. 2003).

3.1.2. Diagram

Based on the analysis of sponge spicules' forms, most of them can be described by a diagram that includes the axis, the stellated and end's mutation (figure 4). Forms are generated according to the diagram.

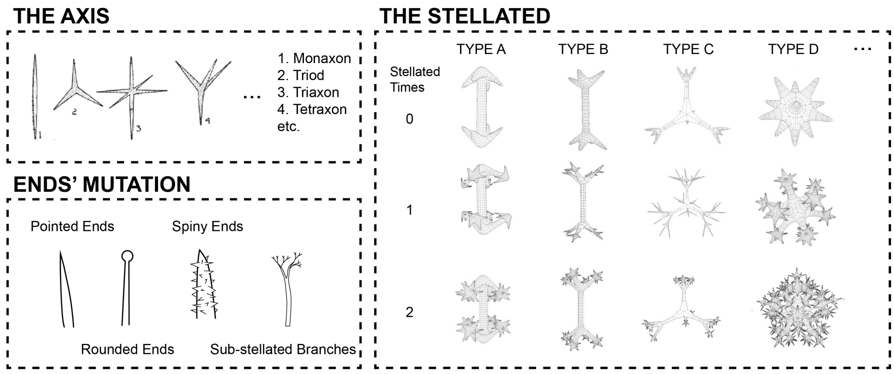

Figure 4. Diagram of sponge spicules' formation, from Thomson (1916).

3.2. IMITATION

Grounded on the diagram of sponge spicules' formation, forms are imitated by programming in Grasshopper. The process includes three stages according to the diagram. That is: Base Faces, Fractal and Ends' Mutation (figure 5).

At the first stage, Base Faces are created from base geometry. The base geometry is Sphere, Donut or Paraboloid (figure5-1A), and it will be tessellated into polygon faces or triangle faces (figure5-1B). Polygon faces are created by intersecting with Voronoi 3D; and triangle faces are derived from a physical method by distributing a set of vertices on the surface. After that, the faces of tessellated geometry are dispatched randomly by setting random numbers or evenly by the checkerboard tool (figure5-1C). Then, some faces are selected to serve as Base Faces which identify the form's symmetry axis.

Secondly, Fractal of branches makes the general form stellated. There are several kinds of branches branching off differently (figure5-2A). And the number of branches depends on that of Base Faces (figure5-2B). Then, several parameters are set to shape into intended stellated forms, such as Loop Number, Child Length and Child Radius (figure5-2C). Loop Number represents the time of branching off, and Child Length and Child Radius separately control the length of child branches and the radius ratio between child branches and parent branches. Also, other parameters build rules to make different stellated forms (figure5-2D). For example, each joint has two or three branches according to the distance to the parent branches (figure5-2D, Three Branches); the more origin's edges are, the more branches the first generation has (figure5-2D, More Branches); each joint branches off in the same physical way as the origin point (figure5-2D, Spherical Joints).

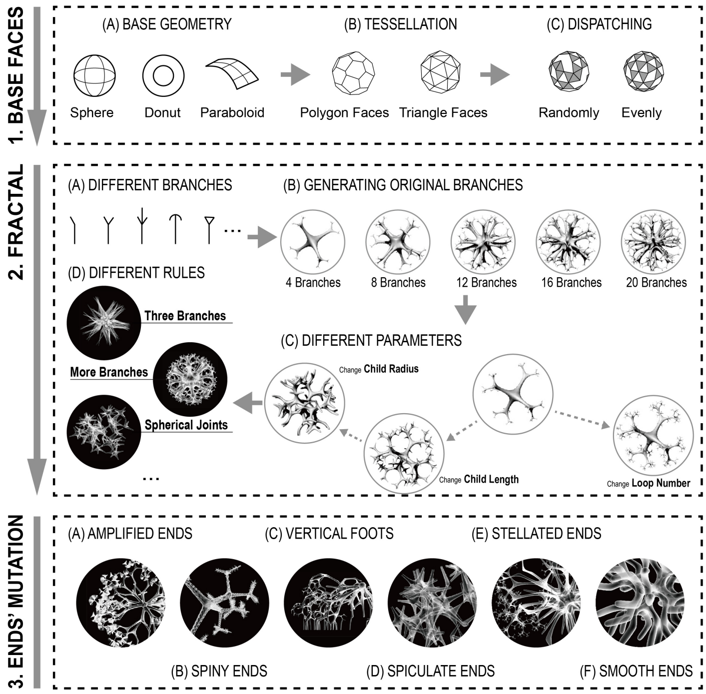

Figure 5. Process of imitation.

At the last stage, Mutation is performed to control the ends' shape of the form. There are six main kinds of Ends' Mutation: Amplified Ends, Spiny Ends, Vertical Foots, Spiculate Ends, Stellated Ends and Smooth Ends (figure5-3). Amplified Ends are amplified like horn mouth; Spiny Ends are similar to the spicules with lots of stiff sharp points; Vertical Foots are selected to touch the ground and provide structural support; Spiculate Ends are branches ending up as points; Stellated Ends are composed of many small stellated branches; Smooth Ends are created by simply smoothing out the branches' ends.

3.3. CREATION

Based on the imitation, different forms are generated by creating different Base Faces, changing the parameters in Fractal of branches, or choosing different types of Ends' Mutation. Besides, interference elements, such as curves and points, are also used for influencing the forms (figure 6-left). For example, when setting a single line, curve or circle as the interference, the form results as asymmetric; when using multiple lines, curves or circles as interferences, the form is symmetric but uneven; when using a set of points as interferences, the form performs as several flowers uniting together.

All in all, grounded on the imitation program, a large number of forms with different features are created by adjusting parameters and adding interferences (figure 6-right).

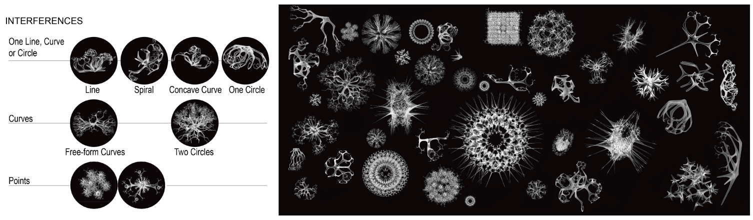

Figure 6. Interferences (left) and a variety of created forms (right).

3.4. APPLICATION

Among lots of created forms, some are potential to be applied into architecture. And the forms are optimized by proper selections in creating Base Faces and End's Mutation, well-adjusted parameters in Fractal, and adding interferences.

As the created forms are unique and attractive, it is possible for them to motivate the negative space in city. For example, a pavilion is designed as an exquisite object under the overpass in city to attract people and diminish the negative space (figure 7-left). While the overpass making the traffic more convenient, it also brought out negative spaces where crimes might happen. These negative spaces will be given a new life with the pavilion.

A ring-like form is selected and optimized as a pavilion. The ring-like pavilion is non-directional and attracts people from all directions. It is also a symbol of equality in city. Actually, the ring-like form is rare in the nature, so the combination of the ring-like form and the spicules' form will arise the curiosity. When lights around the pavilion are on, the lights and shadows create a wonderland-like atmosphere.

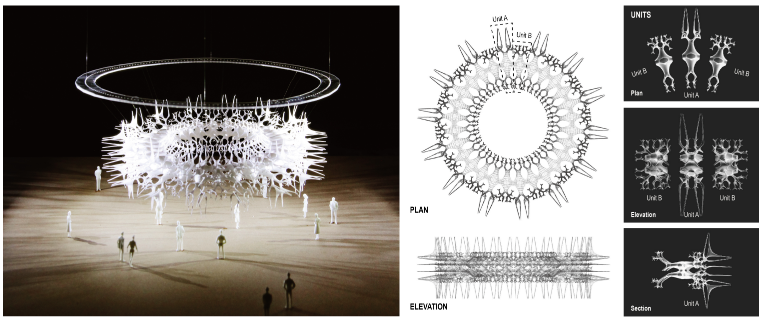

Figure 7. Architectural application as a pavilion and two units.

In order to create the form, firstly, Donut is used as base geometry and tessellated into triangle faces, creating a ring-like and centrosymmetric form. Secondly, Base Faces are generated by dispatching tessellated geometry and alternatively divided into two units: Unit A and Unit B (figure 7-right). Different rules of Fractal are applied to the two units. When growing outward, branches of Unit A protrude the longer spines (higher Child Length), while Unit B branching off more times (higher Loop Number). At last, Spiculate Ends are applied to all branches, adding the concision and power of the pavilion.

3.5. FABRICATION

Taking the pavilion's fabrication as an example, two methods are used: 3D Printing and Turnover Form.

3D Printing is suitable for small and delicate model making. Its quality depends on the printer. The model printed with high precision has perfectly formed details (figure 8-A).

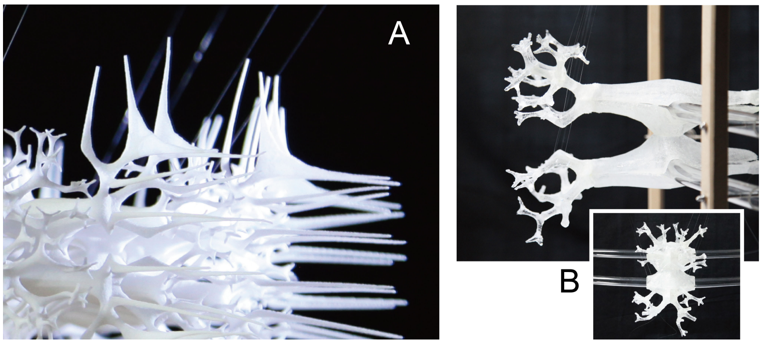

Figure 8. Model made by 3D printing (A) and Unit B made by turnover form (B).

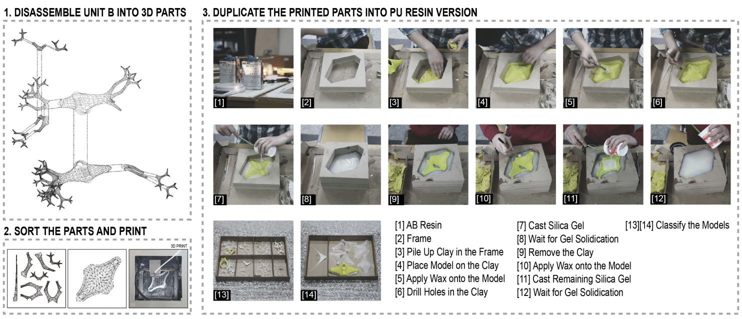

Figure 9. Process of making model by turnover form.

The form can be fabricated by Turnover Form part by part, and this method is much cheaper than 3D Printing. Unit B of the pavilion is made in this way (figure 8-B). First, the unit is disassembled into many 3D parts (figure 9-1), and for the convenience of later process, the joints are designed to be connected without glue. Then, the 3D parts are sorted and each kind of them is 3D printed (figure 9-2). Afterward, in order to get duplicates of identical parts of the units, silica gel is used for mold to duplicate the 3D printed parts into many PU resin versions (figure 9-3). Finally, all parts are assembled together into a unit. And when enough units are made, they can form a whole model together. In this way, a lot of materials and time are saved.

4. Conclusion

The presented approach to bio-based generative design is valid, creative and efficient. Firstly, designers play a significant role in the process, contrary to the previous researches which diminish the effect of designers. The designers' creative ability and aesthetic judgment directly result in the created forms. As for application, designers need to select and optimize a potential result to fit the surroundings. Secondly, the form created by this approach imitates the prototype well and inherits its advantages on the basis of imitation program. Thirdly, not only the biological forms, but their growth mechanisms contribute to the architectural design. Because the imitation is based on the growth mechanisms, the program may simulate an adaptive process similar to the natural adaptation when adding interferences. This inspires the designers to apply the principles of the growth mechanism to architectural optimization. Finally, the approach with five stages is efficient for form generation and can be applied for a variety of biological forms. With the help of the advancing technology, chances are that many complex forms are created and optimized more efficiently. Also, the approach still needs to be developed to adapt to different natural forms better. In future, more and more natural forms would be used as prototype for bio-based generative design by this approach. And the approach will become more complete.

Generative design based on numerous and various biological forms, such as sponge spicules‘ forms, can create endless novel forms by taking the approach stated above. As for sponge spicules, forms created by this approach are varied, adaptable, buildable and harmonious. Because of the high diversity of sponge spicules, forms vary when taking different spicules as the prototype; as there are many parameters and interferences in the program, the form can be optimized by adjusting one or several parameters or changing interferences to serve different purposes; the form derived from spicules also inherits their logical structures, making it possible to be constructed; resembling spicules' features, the form is usually harmonious and complex.

References

Aizenberg, J., Sundar, V.C., Yablon, A.D., Weaver, J.C. and Chen, G.: 2004, Biological glass fibers: Correlation between optical and structural properties, *Proceedings from the National Academy of Sciences of the USA*, 3358-3363.

Aluma, Y., Ilan, M. and Sherman, D.: 2011, Comments on a skeleton design paradigm for a demosponge, *Journal of Structural Biology*, **175**, 415-424.

Andri, E., Gerbaudo, S. and Testa, M.: 2001, Quaternary Siliceous Sponge Spicules in the Western Woodlark Basin, Southwest Pacific (ODP LEG 180), *Proceedings of the Ocean Drilling Program, Scientific Results*.

Baerlecken, D., Swarts, M., Gentry, R. and Wonoto, N.: 2012, Bio-Origami: Form Finding and Evaluation of Origami Structures., *Proceedings of the 30th eCAADe conference*, 497-504.

Bingli, L., Rigby, J. and Zhongde, Z.: 2003, Middle Ordovician Lithistid Sponges from the Bachu-Kalpin Area, Xinjiang, Northwestern China, *The Paleontology Society*, **77**(3), 430-441.

Butler, P.E.: 1961, Morphologic Classification of Sponge Spicules, with Descriptions of Siliceous Spicules fromthe Lower Ordovician Bellefonte Dolomite in Central Pennsylvania, *Journal of Paleontology*, **35**(1), 191-200.

Cárdenas, P. and Rapp, H.T.: 2015, Demosponges from the Northern Mid-Atlantic Ridge shed more light on the diversity and biogeography of North Atlantic deep-sea sponges, *Journal of the Marine Biological Association of the UK*, **95(7)**, 1-42.

Hensel, M.: 2006, Computing Self-Organisation: Environmentally Sensitive Growth Modelling, *Architectural Design*, **76**(2), 12-17.

Imsiecke, G., Steffen, R., Custodio, M., Borojevic, R. and Müller, W.E.G.: 1995, Formation of Spicules by Sclerocytes from the Freshwater Sponge Ephydatia Meulleri in Short-term Cultures in Vitro, *Vitro Cellular & Developmental Biology - Animal*, **31**(7), 528-535.

Kaplinsky, J.: 2006, Biomimicry versus Humanism, *Architectural Design*, **76**(1), 66-71.

Lehnert, H., Stone, R. and Heimler, W.: 2006, New Species Of DeepSea Demosponges (Porifera) From The Aleutian Islands (Alaska, Usa), *Zootaxa, July 2006*.

Liu, K. and Jiang, L.: 2011, Bio-inspired design of multiscale structures for function integration, *Nano Today*, **6**(2), 155-175.

Menges, A.: 2012, Material resourcefulness: activating material information in computational design, *Architectural Design*, **82**(2), 34-43.

Muricy, G., Boury-Esnault, N., Bezac, C. and Vacelet, J.: 1998, Taxonomic revision of the Mediterranean Plakina Schulze (Porifera, Demospongiae, Homoscleromorpha), *Zool J Linn Soc*, **124**, 169–203.

Nsugbe, E.A.O. and Williams, C.J.K.: 2001, The generation of bone-like forms using analytic functions of a complex variable, *Engineering structures*, **23**(1), 22-28.

Peters, T.: 2011, Nature as Measure: The Biomimicry Guild, *Architectural Design*, **81**(6), 44-47.

Rigby, J.K. and Boyd, D.W.: 2004, Sponges from the Park City Formation (Permian) of Wyoming, *Journal of Paleontology*, **78**(1), 71-76.

van Soest, R.W.M., Boury Esnault, N., Vacelet, J., Dohrmann, M., Erpenbeck, D., de Voogd, N.J., Santodomingo, N., Vanhoorne, B., Kelly, M. and Hooper, J.N.A.: 2012, Global Diversity of Sponges (Porifera), *Plos ONE*, **7**(4), e35105.

van Soest, R. 2009, Poliopogon amadou Thomson, 1878, *in* R.W.M. van Soest, N. Boury-Esnault, J.N.A. Hooper, K. Rützler and N.J. de Voogd (eds.), *World Porifera database*.

Thomson, J.A.: 2016, *Outlines of zoology*, Wentworth Press.

Trotta, M.G.: 2011, Bio-inspired design methodology, *International Journal of Information Science*, **1**(1), 1-11.

Vamvakidis, S.: 2007, The Sponge Epidermis: A Study on Minimal Surfaces & Porosity, *Proceedings of the 25th eCAADe conference*, 927-934.

Weinstock, M.: 2006, Self-organisation and material constructions, *Architectural Design*, **76**(2), 34-41.

Weston, M.: 2013, CNC Sponge-forming and Parametric Slip Casting: A Hybridization of Computation and Craft for Architectural Ceramics, *Proceedings of the 33rd ACADIA*, 455-456.