INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED13
19-22 AUGUST 2013, SUNGKYUNKWAN UNIVERSITY, SEOUL, KOREA

SMART TILES SYSTEMS - SPATIAL STRUCTURES BASED ON TILE SYSTEMS WITHOUT EXTERNAL JOINTS

Polina KARAKE TENER, Yasha Jacob GROBMAN
Israel Institute of Technology, Israel

ABSTRACT

The paper presents an ongoing research that examines the potential of creating and implementing infinite spatial tiling systems without external joints. It defines types of possible natural nets that have a potential of tiling, and inherent joining variations. In addition, it presents and discusses a case study in which an infinite spatial tile system was developed, and found its implementation as a Green Partition. Finally, it examines the potential and advantages of such systems.

Keywords: infinite spatial structure, tile system, green wall, inherent joining, structural morphology, topological interlocking

Contact:
Dr. Yasha Jacob Grobman
Technion, Israel Institute of Technology
Faculty of Architecture and Town Planning
Haifa
3200000
Israel
yasha@technion.ac.il

1 INTRODUCTION

The overwhelming diversity of infinite continuous surfaces and tissues in nature is based on an endless number of ordered structures of patterns, which may be represented as infinite polyhedra models, sponge polyhedra, minimal surfaces, etc. (Burt, 2007). To be translated into physical models, however, these geometries must undergo a process of fragmentation into repetitive building blocks, a process that is named in this research "spatial tiling." Until recently, fabrication and assembly constraints allowed tiling only of relatively simple forms, which were supported by additional joints that connected between the tiles. One of the main limitations designers face in the development of such tiling systems has to do with morphology breaking, connecting and assembling (*BCA*[1]). The introduction of parametric design tools for architectural and industrial design, combined with 3D fabrication technologies, has made it possible to explore ways to overcome this limitation (Schodek, 2004).

The standard association of tiles deals mostly with tessellation of two-dimensional patterns and ornaments creating surfaces or screens. Explorations of three-dimensional tiling development dates back to the seventh century, to traditional Islamic geometrical patterns and the infinitely repeating patterns used in *mashrabiya.*[2] These repeating patterns are based on symmetry groups and employed in various architectural decorations around the world (Kaplan& Salesin, 2004).

More recent examples of continuity and potential infinity can be found in the 1950s, in the infinite 3D screens of Erwin Hauer (Hauer, 2007). These screen walls could be defined as the first "component surfaces," which are made of arrays of the same component.

Later, with the introduction of computational design, this idea was developed within the framework of parametric design.[3] In this kind of design, the surface is divided into a grid that is "populated" by one or more components allowing "continuous variation" of those components within the chosen grid. The relationship between the component and its various instances at different points of population within the grid is comparable to the way a single genotype might produce a differentiated population of phenotypes in response to diverse environmental conditions (Shumacher, 2008).

According to the logic of the grid, most of the movements remain on a surface level (2D). In nature, however, spatial tissues develop in three axes following periodic nets. For instance, in the design of crystals, symmetrical building units are linked together in periodic arrays (Delgado Friedrichs, 2006). Thus, it is clear that "it is the business of logic to invent purely artificial structures of elements and relations" (Alexander, 1977). In addition, tiling by itself deals only with the "breaking" part of the BCA process. The other parts are connecting and assembling the system back together. In most cases where spatial tiling is used, elements are joined together with additional joints or connectors, which give the object structural stability. One way to avoid external joining is to employ topological interlocking.[4] This type of joining offers several advantages: easier assembly, higher structural stability at the connection points, one-piece production and lastly, higher geometrical variability.

The following paper presents an ongoing research study that explores the potential of creating and implementing infinite spatial tiling systems that rely on internal joints and/or topological interlocking and do not employ external joints. It suggests a new form-generation method and a new approach to the physical generation of complex systems.

The paper begins with a brief discussion of patterns, possible "tiling nets" and joint variations. It then discusses physical joints and the development of the suggested approach to the methodology of assembling. Finally, it presents a case study in which an infinite spatial tiling system was developed and then implemented as a green partition.

---

[1] BCA process (breaking, connecting, assembling) – a new term coined during the current research that refers to a three-step methodology: "pattern explosion" into separate units; the search for the right connection methodology; and the reassembling of the whole system organically.

[2] *Mashrabiya* – a type of projecting oriel window enclosed with carved wood latticework prevalent in architecture in the Arab world.

[3] Parametric design/Parametricism – a computer-aided architectural design style that refers to designs that change with their input data. These systems give designers more control and capability but require much more comprehensive understanding if they are to be used effectively (Woodbury, 2010) (Shumacher, 2008).

[4] A concept developed in material science. Specially designed solid modules are used to form a structural system without employing glue or mortar. Given fixed boundaries, the elements constrain each other following their topology and form (Estrin, 2003).

2 INFINITE SPATIAL SURFACES AND 3D PATTERNS

In their collective action, large-scale random phenomena create strict, nonrandom regularity (Gnedenko & Kolmogorov, 1968). Whenever a large sample of chaotic elements is taken in hand and marshaled in the order of their magnitude, this unexpected and exceptionally beautiful form of regularity proves to have been latent all along (Frank, 2009). In other words, whenever we look carefully at a chaotic (at first glance) natural system, we need to take into account that a pragmatic order might be hidden inside. Nevertheless, we cannot understand what is happening until we learn to think of probability distributions in terms of their demonstrable information content (Jaynes, 2003). Researchers have tried to understand and represent this hidden complexity in a simple way by dividing and separating the system into smaller parts that can be analyzed individually, so that understanding one unit leads to understanding the whole.

Since in this research terms are borrowed from different fields, the following section will define their meaning in the context of this study:

1. A pattern is an underlying structure that organizes surfaces or structures in a consistent, regular manner. Pattern can be described as a repeating unit of shape or form, but it can also be thought of as the "skeleton" that organizes the parts of a composition (Jirousek, 1995). The last definition is the most relevant, since in this work the inherent structure of the pattern has greater significance than the outside shape.

2. Infinite 3D pattern refers to a pattern in which development occurs in three Cartesian axes, instead of two. This means that the pattern development is not on top of a surface, but rather as 3D net. Examples of this kind of development can be found in infinite polyhedra lattices, periodic sponge surfaces, crystal spatial nets, cellular structures and many more.

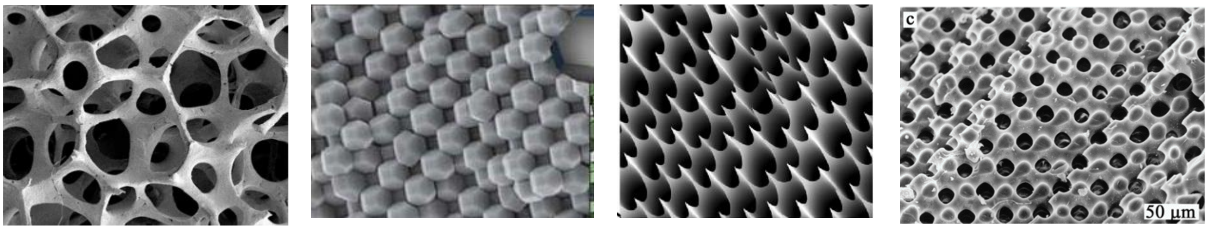


Figure 1. SEM micrographs (from left to right): cellular structure of metal foam; infinite polyhedra of a new octahedron super crystal; bicontinuous membrane of a tapered optic fiber probe; periodic sponge surface of a cross-section of a sea urchin skeletal plate.

Source (from left to right) http://meowmeow0508.wordpress.com/2011/06/09/futuristic-cellular-structure-architecture/; http://www.nature.com/nmat/journal/v11/n2/full/nmat3178 .html; http://spie.org/x44327.xml; http://www1.chem.leeds.ac.uk/FCM/mech%20props.html

3. Skeletal graph is the inherent structure of a 3D pattern or infinite spatial surface. It is built from end points, junction points and connection points. The sequence of connection points between two directly connected skeleton points is called a skeleton branch. For example, in figure 2, *a* and *c* are graphs representing the skeletons in figures *b* and *d* respectively (Bai & Jan Latecki, 2008 p.3).

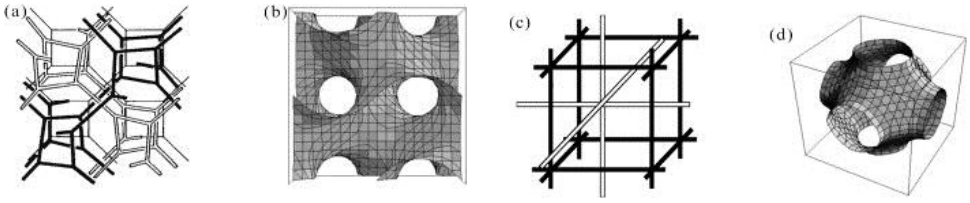


Figure 2. Illustration of the IPMS (Infinite Periodic Minimal Surface) and their graphs (black) and skeletons (white) (a, c). Source: Diele, S. 2002

The field of geometric-topological spatial patterns and shapes and their ordering principles and periodicity characteristics was named "structural morphology" by Prof. Michael Burt in the early 1970s. The field's theoretical framework has been well-developed for a long time and has been successfully applied in different branches of chemistry, material engineering, nanotechnology and computer engineering (Hyde & Schroder, 2003).

In architectural design, the use of structural morphology is mostly found in computer-based parametric design and surface digital modeling because of physical fabrication limitations caused by form irregularity. Since of those structures form complexity, and inaccuracy of fabrication the digital surface forms may significantly differ from their physical prototypes and their fabricated counterparts.

3 RESEARCH METHODOLOGY

The research methodology was based on the following five stages:

1. Defining the desired target element and its characterizations
2. Carrying out three parallel processes: discovering the desired pattern, and studying existing possible enclosure systems and joining systems that could fulfill the defined future product needs
3. Matching between the pattern, the joining system and the enclosure system
4. Creating system "rules" including geometry, symmetry, units variability and joint rotation
5. Beginning the design process

4 BREAKING METHODOLOGY: TILING AND "PATTERN BREAKERS"

"It is the fact of rationalizing highly complex form by breaking it out into smaller, continuous components. If well pursued, tiled objects can be easily designed and assembled" (Oxman, 2010).

Elementary Periodic Region (EPR[5]) contains a complete representation of the entire phenomenon taking place within the "periodic complex" and particularly, representation of the periodic space, its symmetry group, the two complementary (identical) subspaces, the dual lattice-pairs characterizing them, as well as the surface partition in between (Korren, 2007).

The "breaking" approach suggested in this research is based on the following notions:

a) The basic aspiration is not to imitate, but only to supply close representation of desired tissue.
b) Structure and assembly questions are integral parts of basic unit form design.
c) Complexity has to be represented by simplicity.

The current approach suggests a kind of combination between traditional uniform polyhedra assembly, skeletal graphs and mechanical engineering. After a complex pattern is identified, a uniform polyhedron net is chosen to fit this pattern form. Then the dual lattice or the skeletal graph of the structure is created. The basic unit is designed inside those "rigid" limitations but may be freeform. In the final stage, the whole imitating system is assembled together. An example of this process is illustrated in figure 4.

Figure 4. Basic stages of form development (from left to right). Stage 1 – Complex pattern identification (source: http://www1.chem.leeds.ac.uk/FCM/mech%20props.html). Stage 2 – Infinite polyhedra serves as assembly logic Stage 3 – Infinite polyhedra net used as a cage for the constructive skeletal graph of the future basic unit. Stage 4 – Basic unit design inside the "cage." Stage 5 – Inherent joint development, followed by an assembly.

4 JOINING – CONNECTION BETWEEN THE BASIC UNITS WITHOUT EXTERNAL JOINTS

---

[5] EPR is the smallest repetitive cell that is derived from a periodical space using the symmetry operations of the symmetry group that acts on this space.

When discussing physical parametric structures, a differentiation must be made between “building units” and “connectors.” Building units are the parts that create the surface; they may be in any shape or size, or change along the surface they create. Connectors are any additional elements that connect between those units and are not an integral part of them: constructed joints, screws, hinges, mortar or even glue. The following section discusses existing types of joints and the possibility of connecting without using “connectors” or joints.

4.1 Joints

A joint is the location at which two or more structural elements make contact (Medical dictionary, 2011). They are constructed to allow movement or stabilize the structure and provide mechanical support. Joints are usually classified structurally and functionally (Ellis, Standring, Gray, 2005). Structural classification is determined by how the elements connect to each other, while functional classification is determined by the degree of movement between the parts.

4.2 “Joint unit”

The majority of modern spatial structures and other designs use joints as additional external connectors between the main structural units, as was mentioned earlier. This research deals with the potential of developing a “joint unit,” a structural unit containing an integral joint that allows its permanent connection to other units with similar joints. This definition requires a clear differentiation between a valid and a not-valid joint. A joint is valid when:

- It is an integral part of an element.
- It allows two elements to stay connected without any external joint.

4.3 Topological interlocking

In the fields of material engineering and civil engineering, the structural integrity of natural and engineered materials relies on chemical or mechanical bonding between the building blocks of which they consist. In this regard, “materials whose building blocks are not joined, but rather interlocked topologically, possess remarkable mechanical and functional properties. The geometrical possibility of such assemblies opens up interesting avenues in the design of structures” (Dyskin, Estrin, Pasternak, Khor, Kanel-Belov, 2003). In this type of connecting, there are no joints of any kind, but interlocking between parts occurs since to specific form structure of the convex elements and their topology. Assemblies of interlocked elements form flexible layers in which each individual block is held in place by neighboring blocks, while the whole system requires an outer frame. However, these assemblies entail some disadvantages:

- Weak inter-block adhesion leads to creation of propagating cracks.
- Some assemblies are tolerant of missing blocks, while others will collapse.
- The blocks’ rotational degree of freedom may play an important role in the deformation response (Dyskin, Estrin, Kanel-Belov, 2003).

4.4 Valid Joint Types

There are many areas where we can find valid joints (joints that do not require external elements to create the connection), such as the human body and carpentry. These joints can be divided into 3D or 2D types that sometimes allow movement or flexibility, and at other times, stabilize the connection. The following figure categorizes joint types.

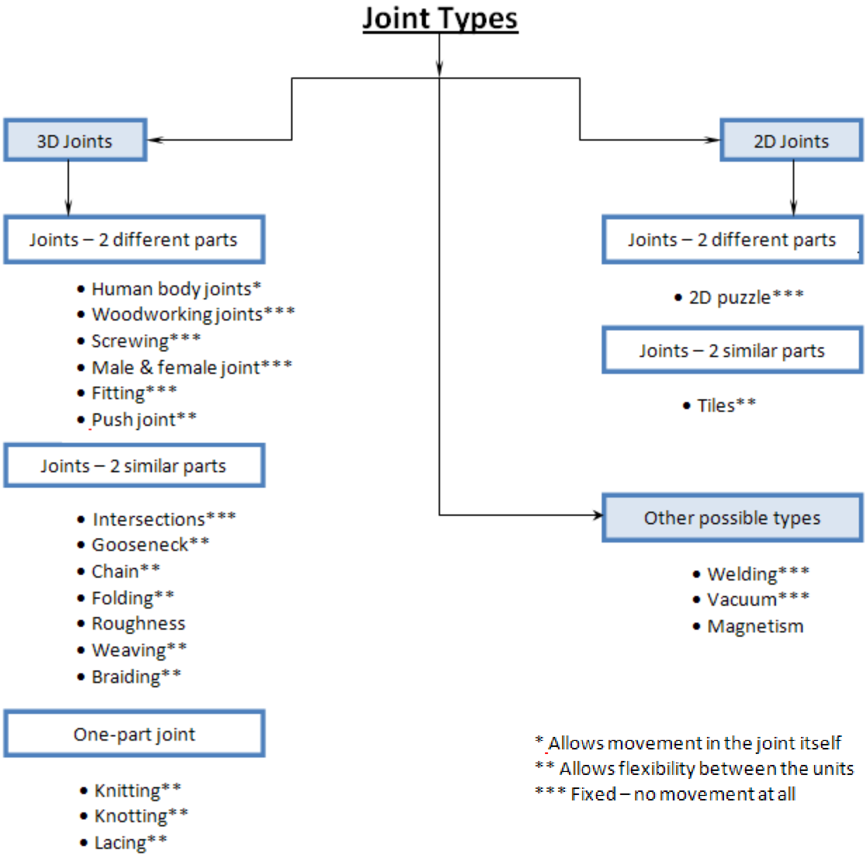


Figure 5. Joint types elimination

5 CASE STUDY: ECO-PARTITION DESIGN

A case study was developed according to the following stages: complex pattern identification, breaking, joining, assembling and finally implementing as an eco-partition, a kind of green wall.[6]

From its initial stages, the eco-partition design must meet some structural requirements:

1. It must be modular, which means it is constructed of repetitive (but possibly variable) module/structural units.
2. It has an internal joint, which means that infinite units may be added and removed.
3. It has plantable units.
4. It must be freestanding, without external supporters such as walls, cables or soil.
5. Its external design has to imitate selected natural tissue.

5.1 Complex pattern identification

Following a survey of complex systems in nature, a sponge structure of a bone tissue was chosen as a starting point in the development of our system. The main reason for this choice was the fact that it is multilayered rather than based on periodic complexity, which posed a great challenge but also a potential for simplified representation of a system based on joints.

---

[6] A "green wall," also commonly referred to as a "vertical garden," is a term used to describe all forms of vegetated wall surfaces or structures. The earliest form of vertical garden dates back some 2,000 years and was found in the Mediterranean region (Kohler, 2008).
Green-wall technologies can be divided into four major categories: green facades, living walls, plantable retaining walls and freestanding eco-partitions.

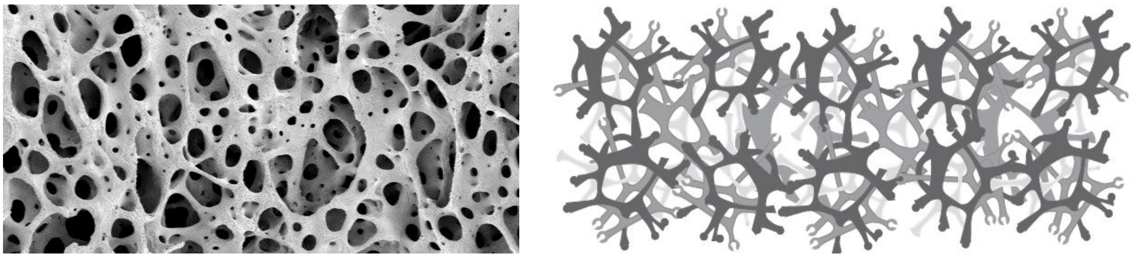


Figure 6. MicroDiscovery bone tissue of a hen magnified x25. Source: http://www.art.com (left). 2D visualization of the initial concept for a possible partition design.

5.2 Joint development

Following the examination of acceptable joints, an “annular snap fit” (ASJ) joint was chosen. Annular snap joints are generally stronger, but require greater assembly force than other snap-fits. Classic examples of ASJs include ballpoint pens with snap-on caps, and the child-resistant cap on Tylenol bottles. This type of snap fit is best for assembling axis-symmetrical (cylindrical) profiles. Accurate size and material deformation calculation are critical when using this kind of fit. The sole “disadvantage” of an ASJ is the fact that it is a linear joint.

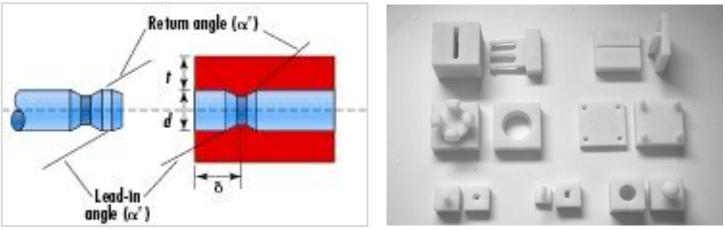


Figure 7. ASJ: d=outside diameter of rigid plug; t=hub wall thickness; §=distance of the snap groove from the end of the hub (left). Source: http://machinedesign.com; 3D prototyping of various joint types (right).

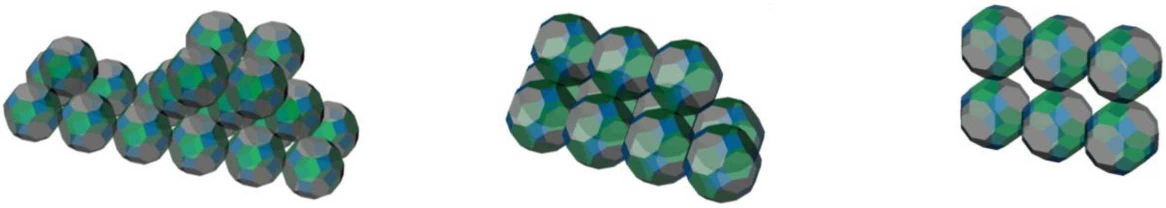
5.3 Polyhedron enclosure

The fact that ASJ can work only as a linear attachment led to the conclusion that the cube is too simple a form, since it has only six faces that can be attached linearly. The number of “branches” in this case would also be six, which is too few for model variability. Since there are a minimum of three “trees” enclosed together, each of the “trees” has to have at least one “branch,” which means that the enclosing form has to have at least three faces that can attach linearly, but no more than 15 since it will become too dense. The polyhedral form called the **great rhombicuboctahedron** (14) was chosen for this research for the following reasons:

- When combined together to form an infinite polyhedron, it still has enough space between its units so that the internal structure can look lighter.
- It is the only polyhedron that derives from the initial form, the cube, and retains the original qualities such as stability.

5.4 Infinite polyhedral organization

The chosen polyhedron contains three types of faces but only the square is 12 faces of the polyhedron, so the attachments between the enclosed units will occur at these faces. Following are the three possible combinations of the infinite polyhedral at these faces:



Option A – octagonal basis

Option B – hexagonal basis

Option C– square basis

Figure 8. Possible organization of the basic structure

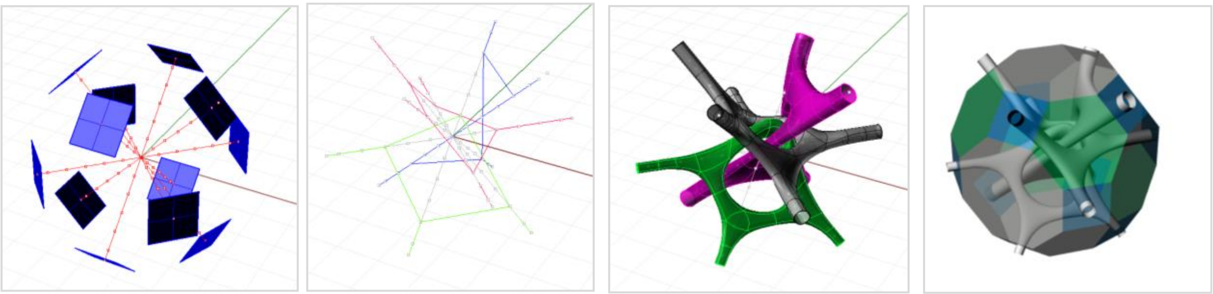


Figure 9. “Trees growing” on the “branches,” designed to be linear at the ends to ensure the annular snap fitting (left). The enclosed unit inside the polyhedron (right)

5.5 Internal modeling

Upon examining the polyhedral organization, it is clear that the octagonal and hexagonal options make the partition twice as wide as the square basis option. However, they leave open the possibility of adding units in any direction, whereas the square option may be added to only at its Y-axis.

The octagonal option was chosen since it has four attachment faces on the ground instead of three, which will create less pressure at each point. In addition, this organization is linear and not diagonal (unlike option B in figure 8), which enables a cleaner design.

5.6 Assembling

In order to check the system’s initial joining assumption, the same unit was repeated in various directions. Initial tests using 3D printed tiles showed that the system seemed to be “working,” but also elicited a few questions, such as:

1. Open ends of the structure that stays unconnected to other units.
2. Establishment and stability problem of the whole system.
3. Whether it is possible to integrate units for plants within the system
4. What would be the structural integrity in various environmental scenarios

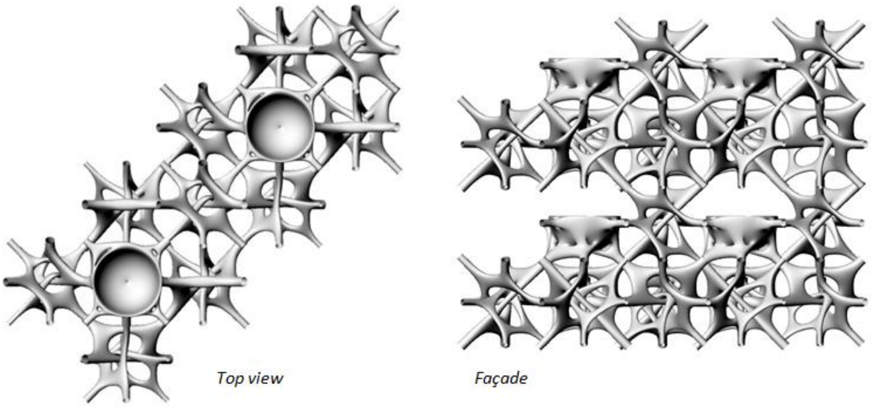


Figure 10. Initial system configuration. Top view (left), front view (right).

5.7 Basement development

To make the composition stable, a base unit was developed using a “one-on-one” method. Each regular unit is supported by single base unit that breaks the polyhedron’s regular geometry. The advantage of this type of organization is the achievement of a clean front line with no “branch waste.” The disadvantage, however, is that one base unit is not as strong since its direction is irregular to the structure.

5.8 Units catalogue

After development of the basic structural unit, the same logic was applied to create various units that differed by function; a basement unit, a pot unit and much more unit variations can be added. The following examples were developed as case studies to examine system functional variability, connectivity and stability. The multiplication and assembly of various units was required to point out weaknesses or strengths in the system as a whole structure, and not only as individual units.

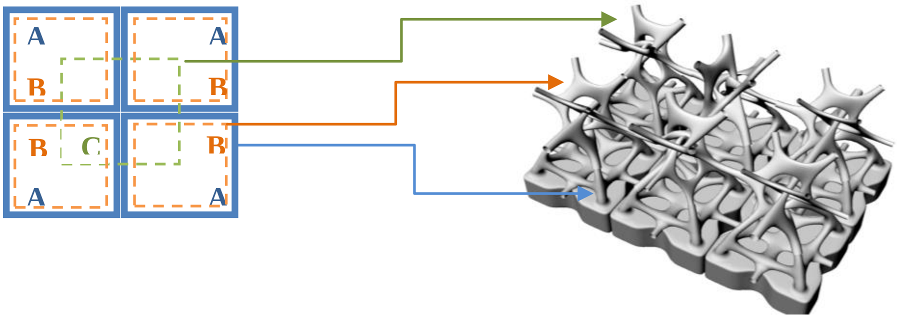


Figure 11. Basement development

Figure 12. Basic units (from left to right): body unit, basement unit, pot unit

6 RESULTS EVALUATION

At this stage of the research, physical models were manufactured using a 3D printer: stable and fluid model types. Connectivity, breakability and stability were checked by assembling and disassembling multiple units in various configurations, and initiating force in several directions in an attempt to destroy or break the assembly. Physical evaluation showed a functionally reliable system that closely imitated the desired initial image. Physical examination showed positive results for connectivity; the chosen joint type was found to be strong and flexible enough to hold the whole structure. However, the specific joint type that was chosen was still an obstacle in form generation since its linearity allowed relatively few enclosing systems, such as an infinite polyhedron. It can be assumed that if other types of joining systems were examined, the variability of the results would be larger. Consequently, it seems that these limitations necessitate examining different joint types or shifting to the use of topological interlocking rather than joints.

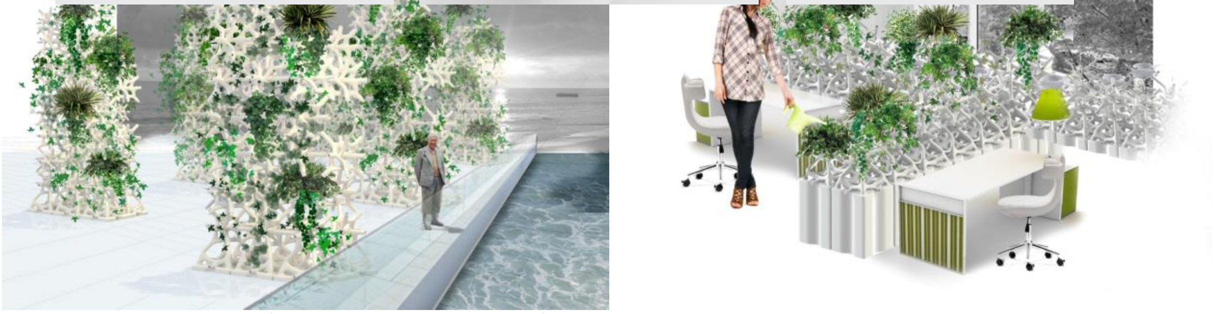


Figure 13. Columns configuration serving as green spaces on floating surfaces (left).
Green partition configuration (right).

7 CONCLUSIONS AND FUTURE RESEARCH

The suggested tiling system has the potential to generate a new level of complexity of form design and assembly. It could help facilitate the construction of structures that previously stayed only on the screen or under the microscope. In comparison to traditional tiling systems, such as Islamic patterns, Erwin Hauer’s work and even parametric design systems, the suggested BCA system appears to have the following advantages:

1. Construction – The use of skeletal graphs as the actual skeleton of the structure follows the constructive logic of the initial tissue and makes it more stable.
2. Adaptation – Breaking the initial tissue into small components with inherent joints, together with infinite polyhedron assembling logic, allows the designer to “grow” the system as an organic element, which can be adapted to various situations.
3. Assembly – The presence of similar joints in all units allows easier assembly in various directions.
4. Variability – The structural logic described above allows creation of a “units bank”- one logic that allows development of various designs.
5. Fabrication, costs and additive elements – Although rapid prototyping is still costly and limited in scale, it seems that in the near future it will be possible to add to the structure or subtract from it an infinite number of elements in any scale, form and material. The ability to construct or disassemble the system on site will make it even cheaper.

The case study and the preliminary research presented in this text represent only the initial steps of the research in this realm. Nevertheless, they seem to show both the plausibility and some of the unique possible capabilities of the proposed approach. The next stage of the research will concentrate on a performance and construction examination through working prototypes of various scenarios for smart tiling systems, in various scales and materials.

REFERENCES

Alexander, C. 1977. *A Pattern Language: Towns, Buildings, Construction,* New York: Oxford University Press.

Bai, X. & Latecki, L.J. 2008. “Path similarity skeleton graph matching,” *IEEE Transactions on Pattern Analysis and Machine Intelligence,* vol. 30, no. 7, pp. 1282-1292.

Burt, M. 2007. “Periodic sponge polyhedra in nature and in the realm of the theoretically imaginable,” *VISMATH,* vol. 9.

Delgado-Friedrichs, O., O’Keeffe, M. & Yaghi, O.M. 2006. “Three-periodic nets and tilings: edge-transitive binodal structures,” *Acta Crystallographica Section A,* vol. 62, pp. 350-355.

Dyskin, A., Estrin, Y., Kanel-Belov, A., 2003. “Topological interlocking of platonic solids: a way to new materials and structures,” *Philosophical Magazine Letters,* vol. 83, no. 3, pp. 197-203.

Ellis, H., Standring, S. & Gray, H.D. 2005. *Gray’s anatomy: the anatomical basis of clinical practice,* St. Louis; Elsevier Churchill Livingstone.

Frank, S.A. 2009. “The common patterns of nature,” *Journal of Evolutionary Biology,* vol. 22, no. 8, pp. 1563-1585.

Gnedenko, B.V. & Kolmogorov, A.N. 1968. *Limit Distributions for Sums of Independent Random Variables,* Reading, MA: Addison-Wesley.

Hauer, E. 2004. *Continua-Architectural screens and walls,* New York; Princeton Architectural Press.

Hyde, S. & Schroder, G. 2003. “Novel surfactant mesostructural topologies: between lamellae and columnar (hexagonal) forms,” *Current Opinion in Colloid & Interface Science,* vol. 8, no. 1, pp. 5-14.

Jaynes, E.T. 2003. *Probability Theory: The Logic of Science,* New York; Cambridge University Press.

Jirousek, C. 1995. *Art, Design, and Visual Thinking,* Ithaca, NY: Cornell University.

Kaplan, C.S. & Salesin, D.H. 2004. “Islamic Star Patterns in Absolute Geometry,” *ACM Transactions on Graphics,* vol. 23, no. 2.

Kohler, M. 2008. “Green facades – a view back and some visions,” *Urban Ecosystems,* vol. 11, pp. 423-436.

Korren, A. 2007. “Space Partition by 2-Manifold Surfaces and their Architectural Applications,” *Symmetry: Art and Science,* Buenos Aires Congress, p. 289.

Oxman, N. 2010. “Structuring materiality: Design fabrication of heterogeneous materials,” *Architectural Design,* vol. 80, issue 4 (July-Aug), pp.78-85.

Schumacher, P., 2008. *Parametricism as Style – Parametricist Manifesto,* Dark Side Club 1, 11th Architecture Biennale, Venice.

Schodek, Daniel L. 2004. *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design,* Hoboken, NJ: Wiley. Print.

Siegmar,D. 2002. “On thermotropic cubic mesophases,” Institute of Physical-Chemistry, Martin Luther University Halle-Wittenberg.

Woodbury, R.F. 2010. *Elements of Parametric Design,* New York: Taylore & Francis Group.