

Generative Approaches in Tower Design Algorithms for the Integration of Tower Subsystems

Elif Erdine // Architectural Association

Abstract

“Generative Processes in Tower Design”, a PhD thesis in Architectural Design currently being developed at the Architectural Association (AA), proposes a new systematic design approach towards the re-creation of an architectural typology which has maintained a stable organizational structure since the end of the 19th century, the tower. The paper argues that the tower needs to respond to its environment by changing from a closed building typology towards a heterogeneous, differentiated open system that can adapt to the changing conditions within and around it. This argument is supported by focusing on the analogies and principles of specific biological examples in order to propose computationally-generated self-organizing systems. The goal of analyzing these models is to integrate their structural and geometrical characteristics with the aim of overcoming high lateral loading conditions in towers, as well as elaborating on the existence of multi-functionality and integration throughout the subsystems of the tower. A series of computational models which abstract the biological properties and articulate them with a generative approach through the use of agent-based systems are implemented according to designated evaluation criteria. The research posits new forms of design knowledge and practice by developing a design methodology that is set between architecture, biology, and computation.

Keywords

Tower; biomimetics; integration; differentiation; generative algorithms.

Note

This article is a newer version of a recent paper which will be published in eCAADe 2013 Conference Proceedings.

Introduction

“Not only biology has become indispensable for building but building for biology.”
(Otto, 1971)

The tower typology preserves the vision and ambitions of modern cultural and technological production. As the symbol of Modernism, the tower agenda is still defined today by standardization, repetition, segmentation, and orthogonal grid based structures. This agenda has instigated the potential of the tower to be reduced to binary axioms, such as tower and city, circulation and habitation, structure and skin (Aiello, 2008). Combined with the global economic and cultural motives for the tower, which are emphasized through parameters such as dense urban contexts, high real estate values, commercial opportunity, corporate demand, and iconic presence, the tower has become a self-referential object that has limited connection to its urban context.

In contemporary urban conditions, where the various social, economic, cultural and artistic systems are interacting in a constant flux of density and differentiation, the tower needs to respond to its current environment by changing from a closed building typology of repetitive floor plates towards a heterogeneous, differentiated open system that can adapt to the changing conditions surrounding it. Whether it is programmed for a single function or multiple uses, the contemporary paradigm of architecture will expect a differentiation of the tower along its vertical axis, its circumference, and within its volume that are interdependent with each other.

“Generative Processes in Tower Design” focuses on the principles of biological models in order to propose computationally generated dynamic systems for the tower typology, with the aim of achieving an integrated model for the tower subsystems that can coherently adapt to their climatic and cultural context.

The development of tall buildings in contemporary practices relates closely with structural developments. This is due to the fact that ‘tallness’ amplifies the significance of different loading conditions that act on a building. Due to the impact of loading in tall buildings, the structure of a tall building bears a significant role from the outset of the design process. In comparison with lower buildings, tall buildings are exposed to higher vertical loads, and more importantly higher lateral loads, mainly due to the wind stresses. The primary structural skeleton of tall building acts as a vertical cantilever beam with its base fixed on the ground.

Within the context of this research, tower is understood as a building system under considerable lateral loading conditions, with slenderness ratio ranging between six to eight. The focus is based on treating the tower as an inhabitable structure, whereby its footprint and internal spatial organization should allow for various programmatic requirements. In this respect, the correlation of footprint to height and how this correlation is influenced by lateral loading become more influential in the design research process rather than stating a predetermined height for the tower.

Current State of the Tower

From the end of the 19th century till the 1960s, the common practice of constructing tall buildings was the rigid frame with wind bracing, which resulted in the over-design of structure due to the excessive use of structural material, thereby causing it economically not feasible. Structural engineer and architect Fazlur Khan introduced the notion of the ‘premium for height’ for tall buildings in

1960's, and in 1969 classified their structural systems in relation to various techniques of resisting lateral loads for steel and concrete buildings. This initial classification according to different material systems introduced for the very first time a differentiated approach into examining tower structural systems with the aim of increasing tallness and stiffness while decreasing the amount of material. Due to the developments in structural systems in the last decades in conjunction with progressive material systems, construction technologies, and computer simulations, a refined classification has been proposed by Mir M. Ali and Kyoung Sun Moon, based on the first classification proposed by Khan. Accordingly, structural systems for tall buildings can be divided into two categories: interior structures and exterior structures (Ali, M.M. and Moon, K.S., 2007).

The development of tower structural systems reveal that even though there has been a continuous differentiation of material organization with the purpose of increasing height and rigidity simultaneously by decreasing material usage, each distinct tower system has a homogeneous and repetitive organization. The structural loading along the height of the tower varies drastically from bottom to top; however, the change in loading conditions is not reflected along the vertical axis of the tower as formal topological variation. This rigid and repetitive modality, characteristic of the Modernistic paradigm, has prevented any kind of rational transition within a specific type of tower structural system.

Furthermore, the notion of differentiation has not been integrated with the other subsystems of the tower. The differentiation of material organization in the tower structure has been limited to one subsystem only, the structure. As such, tower structural systems have developed with single objective optimization. Other performance related capacities, such as circulation, facade, and environmental aspects, have developed independently of the material organization of the tower structure. Moreover, the tower structure has become devoid of responding to the spatial differentiation that takes place within, acting merely as a homogenous container. It has not responded to the changes and shifts in its programmatic diversity, which in effect influences circulation, façade-related, and environmental differentiation. This additive approach, where each subsystem is considered as a separate layer, results in the inefficient and excessive use of tower material organization. In this regard, the current knowledge on tower design lacks an integrated approach towards its subsystems on two major levels, the first being the "topological variation" within one subsystem, and the second being the "inter-system differentiation" taking place between multiple systems. Therefore, it is necessary to explore and learn from existing systems which are capable of integration and co-adaptation.

The current organization of the tower subsystems, which are classified into five groups as the structural skeleton, habitable surfaces, circulation/navigation system, envelope, and environmental systems, have developed in an independent manner. The subsystems are partially related to each other in terms of taking minor secondary functionalities that primarily belong to another subsystem, as in the case of floor slabs having additional structural capacity. However, the potential of the additional capacity has not been exploited such that it can become a fully integrated part of the primary subsystem. As such, the conflation between the subsystems needs to be analyzed and explored with an innovative vision.

Biology in Architecture

There has been a broad body of research work on the relationship between nature and architecture throughout history. Biology particularly serves as a main resource for architecture due to the strong relationship between form, material, and function in its inherent formation. The analogies between biology and architecture can be classified into two groups, the first acting as the mimicry of biological forms and the second acting as the mimicry of biological materials, structures, and processes (Coucerio, 2005). Within the context of this research, processes of self-organization and material configurations have been examined as analogous models towards the generation of an integrated approach for tower subsystems.

Natural systems are complex organizations, characterized by the spontaneous emergence of interdependent subsystems, ranging from the cellular to the global level that can adapt to various external stimuli. The subsystems can carry on distinct functions at once due to the principles of differentiation and redundancy. In the case of plants, the plant stem can undertake structural, transportation, and storage functions due to the variation of its sections along its length and the ordering of its basic materials into complex hierarchical arrangements. The organization of materials in interrelated semi-autonomous hierarchies by means of redundancy and differentiation leads to the integration of distinct functional systems throughout the stem. On the contrary, in current architectural practices, the sub-systems of the tower, such as façade, structure, floors, roof, services, carry on specific functions. These subsystems are separated from each other with boundaries and joints which prevent the material and functional continuity between them. The subsystems mostly perform their entitled functions; they do not have the balancing capacity of executing additional tasks, whereby they can only act as homogeneous entities.

Regarding the above mentioned explorations as a foundation for the research area, specific biological analogies which have been studied in this work include the mechanical properties of the bamboo stem and the geometrical properties of minimal detours systems. The common feature that these models share is their property of self-organization as well as their unique geometrical and structural properties.

Bamboo Stem

The mechanical properties of the bamboo stem prove to be beneficial for the tower structural system in various ways. Bamboo is formed of long cellulose fibers embedded in a ligneous matrix. The fiber distribution along the bamboo stem is differentiated along the height and circumference; the distribution of fibers is more uniform at the base compared with the middle and top portions. This occurrence can be explained by the fact that bamboo needs to carry maximum bending stress caused by wind and its own weight at the base (Koshrow, 2005). The radial differentiation of fibre density, increasing from centre to periphery matches the distribution of bending stresses. The phenomenon of differentiated distribution of fibers according to applied forces can serve as a model for the distribution of structural members of towers along the vertical axis and the circumference.

The bamboo stem comprises internodes and nodes. The stem itself is a hollow cylindrical shell along which the nodes correspond to the internal diaphragms, described as

transversal connectors located throughout the height of the bamboo stem. The diameter of the stem changes slightly at the nodes, which also function as location for new growth. Internodes are located in between the nodes, denoting the hollow portions surrounded by the culm wall. The diaphragms supply resistance against the buckling of culm wall over the height of the stem. There are two major outcomes of the material in the stem being positioned at the outermost location from the vertical axis. The material deposition enables greatest bending resistance as well as causing gravity loads to be carried only on the outside skin of the stem, minimizing overall weight and preventing uplift due to lateral loads (Sarkisian, M., Lee, P., Long, E., Shook, D., 2010).

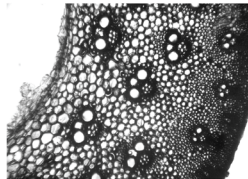
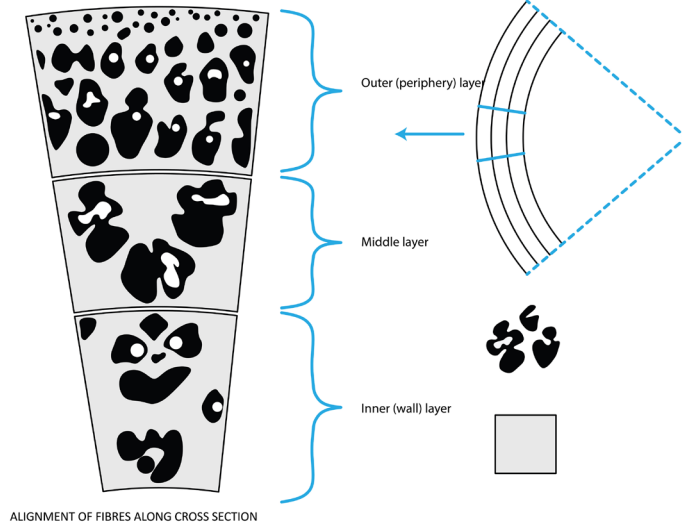
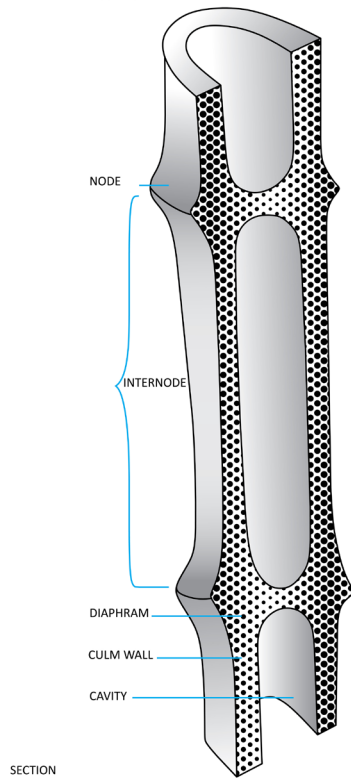
The position of the diaphragms, internode diameter, and the culm wall thickness are dependent on each other. The geometric relationships between these entities have been described by Jules Janssen (Janssen, 1991). The equations below summarize the correlations which can be observed in many bamboo species (Sarkisian, M., Lee, P., Long, E., Shook, D., 2010):

<p>Internode Number</p> $x_n = n \times 100 \div N$
<p>Internode Length</p> $y_{n1} = 25.13 + 4.8080 x_n - 0.0774 x_n^2 \text{ (below mid-height)}$ $y_{n2} = 178.84 - 2.3927 x_n + 0.0068 x_n^2 \text{ (above mid-height)}$
<p>Internode Diameter</p> $d_{n1} = 97.5 + 0.212 x_n + 0.016 x_n^2 \text{ (below mid-height)}$ $d_{n2} = 178.84 - 2.3927 x_n + 0.0068 x_n^2 \text{ (above mid-height)}$
<p>Wall Thickness</p> $t = 35 + 0.0181(x_n - 35)^{1.9}$

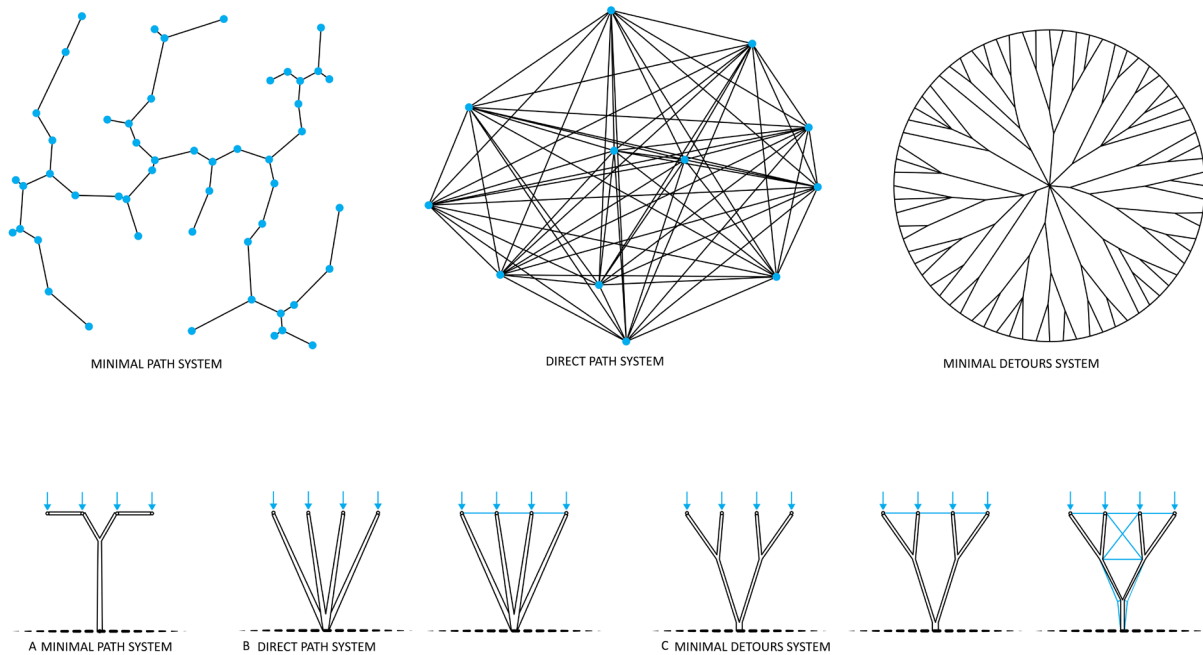
In these equations, x_n is the internode number, n is a shaping parameter; N is the height of the structure; y_n is the internode length; d_n is the internode diameter; t is the wall thickness. The information embedded in these relationships can be generalized in relation to the various forces the bamboo is subjected to. As the lateral loading condition and the weight from gravity is highest at the base of the stem, the internode heights at the base become shorter than the mid-height. As such, smaller internode heights increase moment-carrying capacity and buckling resistance. Above the mid-height of the culm, the internode heights decrease once more in proportion to the internode diameter as a reaction to increasing lateral loads (Sarkisian, M., Lee, P., Long, E., Shook, D., 2010).

The above-described morphological relationships of bamboo are applied to the structure of the tower on a global scale. The diaphragms of the bamboo stem can serve as an analogous model for an outrigger system in a tower. The position and the diameters of the outriggers can be predicted by using the above equations in order to resist lateral loading conditions in an effective manner. Moreover, the structural members of the tower can be differentiated in terms of amount and sectional size with regards to the changing loading conditions. However, a significant difference needs to be noted when the diaphragms of the bamboo are to be regarded as an analogous model to the outriggers of the tower. As an inhabitable structure, the tower is also under the effect of live loads,

BAMBOO PROPERTIES

**Figure 1.**

Bamboo cross section and horizontal sections.

**Figure 2.**

Differences between optimized path systems.

a dynamic type of load which is dependent on building use, such as human movements and snow loads. In this respect, since the outriggers are also exposed to live loads, their fibers/ structural members need to be designed by taking into consideration this extra

Minimal Detours System

Extensive research on branching structures has been pioneered by Frei Otto and his team as the 'Biology and Building' Working Group at the Institute for Lightweight Structures, Stuttgart University during the end of 1980's. The focus of this research has been to investigate the potential ways of covering large spans with optimized branched constructions. In this study, concentration has been kept on regulating the material organization of the system as a direct outcome of the force fields acting upon it, so that the load bearing capacity is increased while the amount of material deposition is decreased. As such, form-finding was investigated as a "single objective optimization" (Hensel, M. and Menges, A., 2009).

Branched constructions can be described as three dimensional supporting structures used in various material systems, such as steel, wood, and concrete. This structural system offers more stability than conventional beam structures as beam structures are more likely to overturn as a result of wind and earthquakes. Moreover, the use of branched structures enables the use of thinner structural members and covering larger spans (Otto, F. and Rasch, B., 1995).

The properties of branched constructions have been explored by Frei Otto and his team in order to formulate methods of transporting forces over a given distance in the most effective way. The first method, minimal path system, links given points with detours to produce the least overall distance. In nature, the minimal path system can be observed in the self-formation of soap films. Structurally, this system is less effective for the transport of forces as the outer support arms are loaded in bending. The second method, direct path system, connects every given point with a straight line to each other with no detours. Through this method, the forces are transported on the shortest possible path, but the overall path length increases drastically. This system becomes more effective if the points of force application are connected with beam ties so that the bars are compression loaded. The third method, namely the minimal detours system, can be viewed as a negotiation between the minimal path and the direct path systems. Synthetic analogy research about this method has been carried out by exploring the self-formation processes in moistened thread networks. Reviewing this method in a structural context yields the result that the forces to be transported are more optimized due to the concentration of paths, increasing the buckling resistance of structural members. Effectiveness of the system is increased more if the points of force application are connected with a beam tie. As a result, branched structures generated with minimal detours system use less material in a more effective manner than the ones generated with direct path system (Otto, F. and Rasch, B., 1995).

In nature, branched structures can be found in abundance throughout various plant systems. Materialized direct path systems can be observed in umbels, and materialized minimal detours systems can be viewed in bushes and shrubs. The difference between branched constructions in architecture and nature lies in functionality. Whereas the

branched structures built by humans are mainly designed to carry a structural function, the branched constructions of nature have the property of multi-functionality. In the case of plants, the branches need to transport water, minerals and products of photosynthesis for survival as well as maintain the necessary structural resistance against the various forces applied to the leaves (Otto, F. and Rasch, B., 1995).

The combination of the effective properties of the minimal detours system and the multi-functional quality found in natural branched constructions can be merged to serve as an analogous model for the structural components of the tower. Following the global geometrical rules of the bamboo stem described above, the structural members can be defined geometrically in relation to the mathematical rules of branching systems in order to devise a design method where the organization of structural members is set up to resist the loading conditions of the tower in the most effective way. As such, a hierarchical design system is proposed where the properties of the bamboo stem and the properties of branching structures are integrated on different levels.

Agent-Based Model

The computational setup for the design explorations reflects the characteristics of self-organization described above through various biological models. As a systematic approach, in biological systems self-organization refers to the process where pattern at the global level emerges from the interaction between lower-level components. The rules specifying the interactions between lower-level components rise from local information, without the interference of external directing instructions. The transition of this phenomenon from the biological world to the digital paradigm has been realized by swarm intelligence. Swarm intelligence describes the behavior exerted by natural or artificial self-organized systems, which are made up of boids/agents interacting locally with one other and their environment. These interactions lead to the emergence of complex systems demonstrating intelligent behavior on a global level. The simulation of swarm intelligence is realized by agent-based models, which are computational algorithms created to simulate the interactions of local boids/agents in order to evaluate their complex behavior. The term "boid" was first coined by Craig Reynolds in 1986 when he created a flocking algorithm for generic creatures.

An agent-based model has been devised for tower design explorations in the open source environment Processing. As an object-oriented programming language (OOP), Processing allows for the generation of procedures / objects on a local level (class) which can then be interacted with each other according to set rules in order to produce emergent patterns on a global level. In this respect, initially the global geometrical constraints have been defined through the setting of the slenderness ratio, which can range from six to eight. The height of the tower is calculated according to the defined base radius and slenderness ratio. On a local level, all the agents in the system interact with each other according to flocking principles, namely separation, alignment, and cohesion. Additional flocking rules in relation to the vertical speed of growth and rotational force of agents are assigned.

The primary agent setup is comprised of two sets of agent groups which form two helical intertwined structural frames. The main motive behind creating two structural

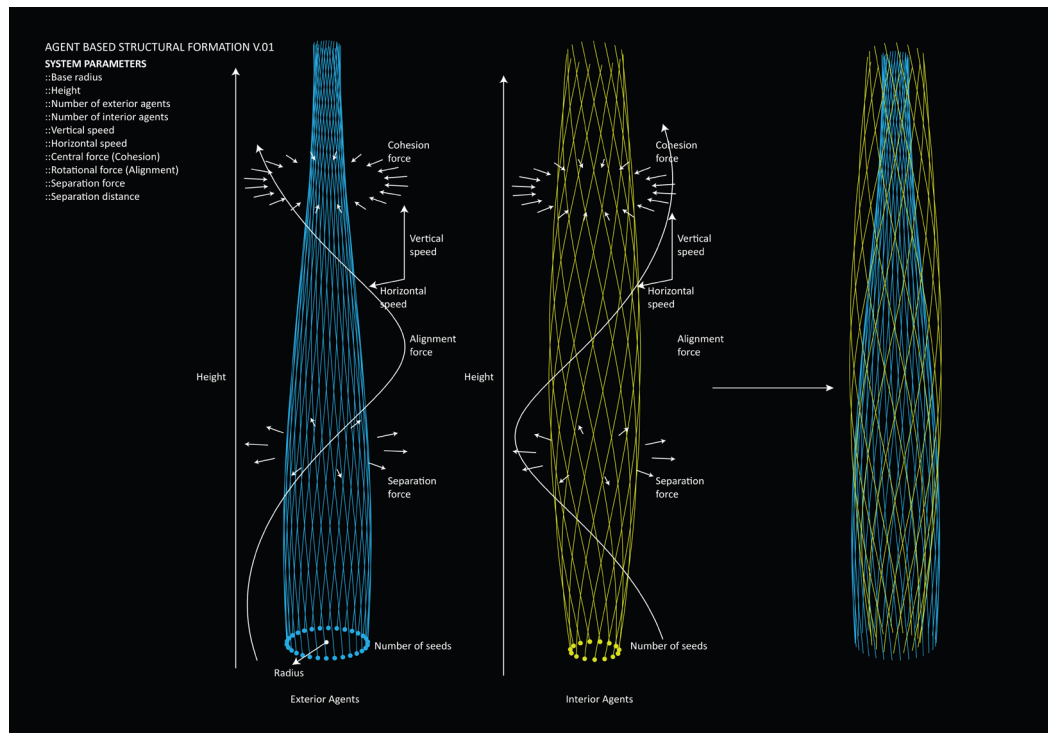


Figure 3.
Agent-based structural
formation model.

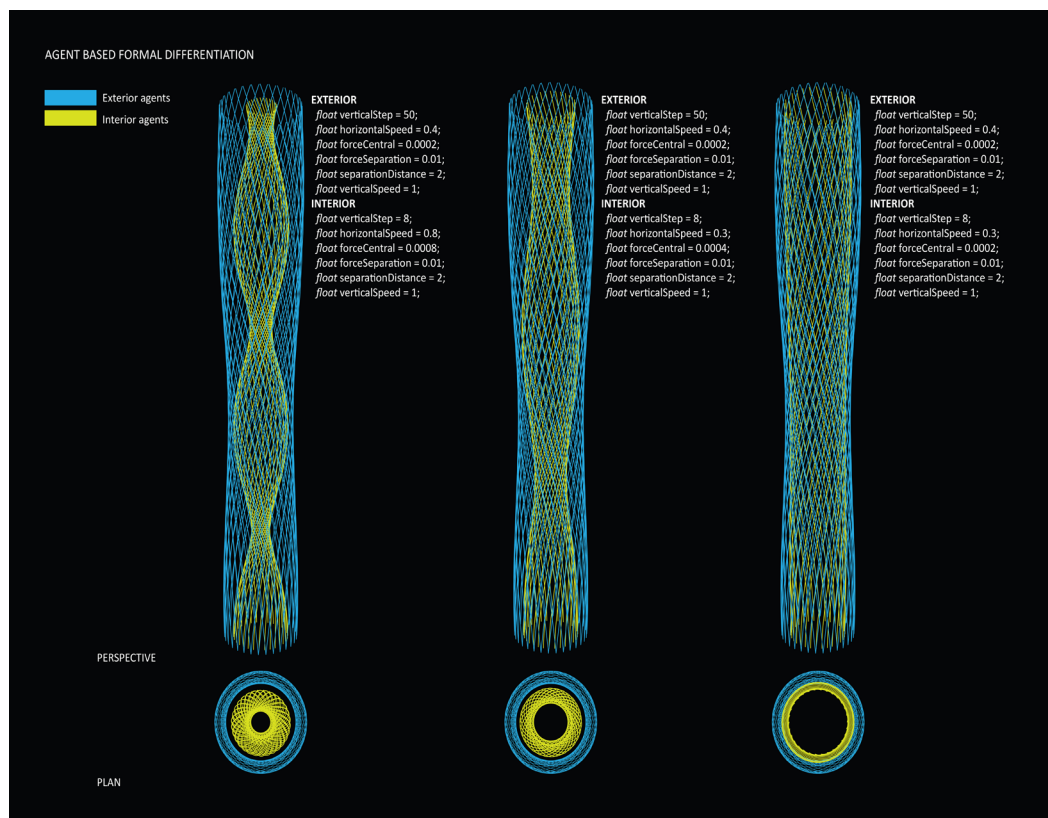


Figure 4
Agent-based Formal
Differentiation.

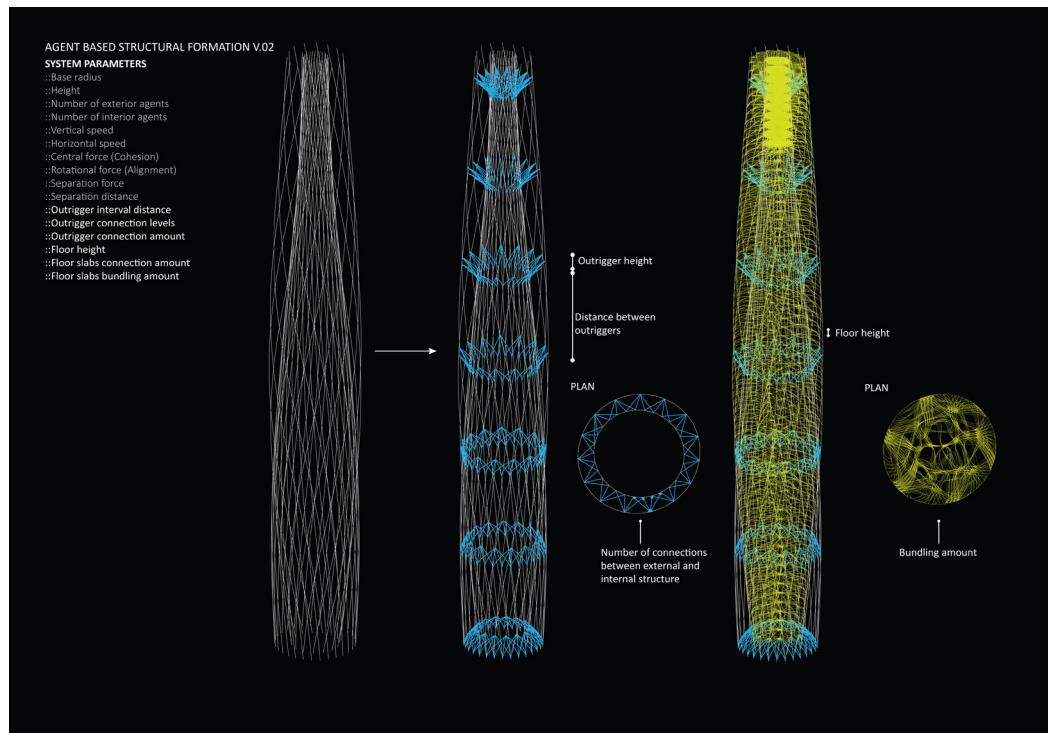


Figure 5.
 Generation of outrigger system and floor plates.

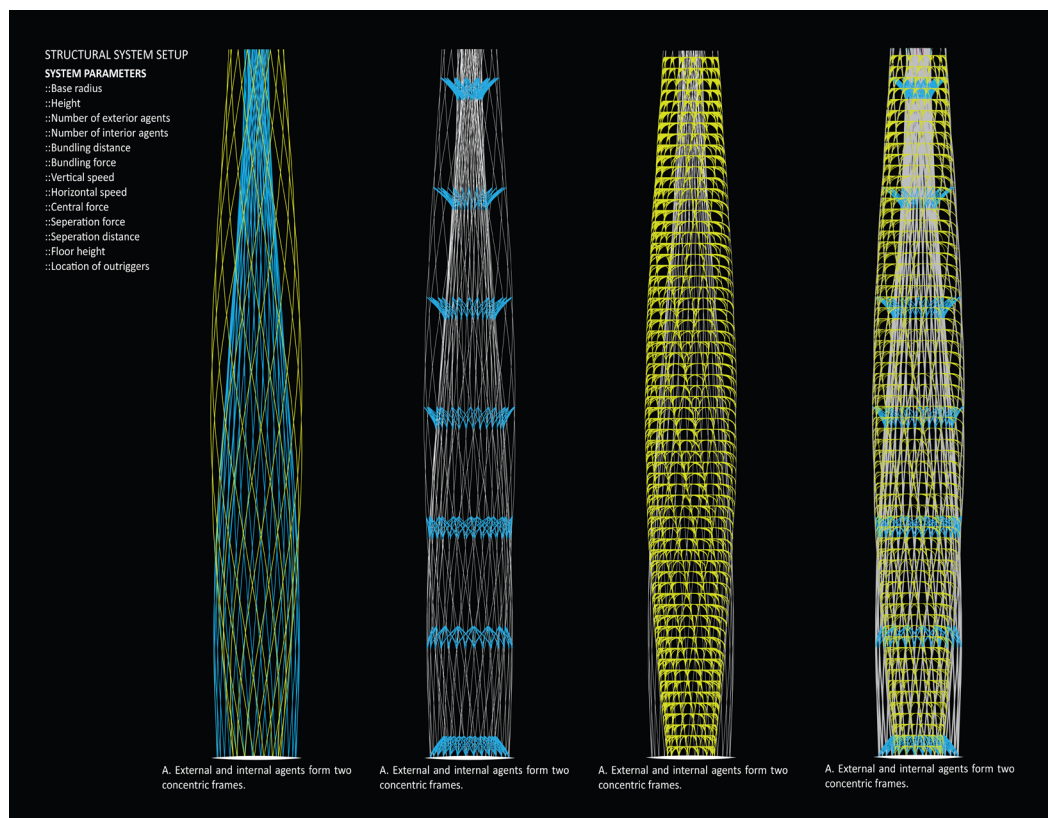


Figure 6
 Vertical structure,
 outrigger system
 and lateral structural
 system.

frames instead of a singular one is to infuse the structures with differentiation and redundancy by assigning related but discrete functionalities to each of them. Moreover, a double structural frame bears the potential of generating different spatial configurations in relation to the frequency and location of intertwining.

The helical double structure serves as a major framework for the generation of floor slab members, outriggers, and vertical circulation. As the agents grow vertically to form the double structure, they branch out to form the floor slabs using the specified floor heights for discrete programmes. The positioning of the outriggers throughout the height of the tower is defined according to the above described geometrical relationship between the bamboo stem internodes and heights. The outriggers serve to connect the external and internal structural frames, whereas the floor slabs are tied to the internal structure. While the external and internal structures act in compression, the floor slabs and outriggers act in tension. The double structure and the floor slabs / outriggers are interdependent systems, meaning the floor slabs and outriggers prevent the double structure from collapsing while the double structure, in turn, supports these horizontal members. Since the distribution of loads takes place over the entire fibrous members of the tower, vertical elevators can be located throughout the floor plate in desired locations. This approach, where the vertical structural members, horizontal structural members, and floor plates are generated together in a seamless fibrous fashion, presents a significant shift from the traditional method of relying on a rigid internal core and a series of columns for stability.

As the agent-based system builds up the double structure, vertical circulation, outriggers and floor slabs simultaneously, a bundling algorithm calculates the minimal detours system necessary to concentrate the fibrous paths and thereby optimize the forces traveling throughout the tower. The percentage of bundling can be manipulated according to the individual subsystems, the vertical position of the members, or the location of the members along the circumference of the tower. The minimal detours system has the potential to manipulate the behavior of the members on a local level, creating ways of fine-tuning the structural performance as well as defining various spatial configurations according to transparency levels, orientation, and views, thereby refining the interface between the tower and its contextual environment. As such, form-finding through the minimal detours system can move away from acting as a 'single objective optimization' and progress towards becoming a 'multi-parameter integration' tool due to its coexisting structural and spatial attributes.

Conclusions

Currently, design explorations for the integration of structure, floor slabs, and vertical circulation as one cluster of subsystems are being conducted. Structural analysis is being carried on via the FEA software Strand 7. The results of the structural analysis will serve as a feedback mechanism in order to refine the positioning and number of floor slab and outrigger elements. After this stage, the integration of structure, façade and environmental systems as another cluster of subsystems will be investigated through the agent-based system by setting up respective parameters. In this way, it is anticipated that the final integration of the two clusters of subsystems will be achieved by keeping the structural parameters the same for both clusters.

At this stage of the research, it has been observed that the behavior of the various subsystems can be manipulated simultaneously by modifying the parameters which coordinate the local interactions between agents. By using agent-based systems as a computational tool, a hierarchical systematic approach displaying the quality of emergence from lower level organizations, tower subsystems, towards a higher level integrated tower design can be devised. The biological analogous models which are being explored can serve as unique models in the generation of “topological variation” throughout the height and circumference of a singular subsystem. Moreover, these models can also perform to enable the “inter-system differentiation” taking place between multiple systems owing to their inherent geometrical and material organizations.

The research aims to reconfigure all the main elements of contemporary tower design, which in turn will liberate the fixed typology of the tower towards a novel tower system that is described with the qualities of adaptation, integration, and fluidity. Through this research, the major questions that are sought to be answered are: What can we learn from biological processes in order to form an integrated design approach that can create context-specific tower design which operates on multiple levels? Can we devise an evolutionary system for tower design which can continuously adapt to its environment? As such, the research aims to bring out new forms of design knowledge in the area of tower research by merging architecture, biology, and computation.

References

- Aiello, C. ed., 2008. *Evolvo: Skyscraper for the XXI Century*. USA: Evolo Publishing.
- Ali, M.M. and Moon, K.S., 2007. Structural Developments in Tall Buildings: Current Trends and Future Prospects. *Architectural Science Review*, Volume 50.3, pp.205-223.
- Coucerio, M., 2005. Architecture and Biological Analogies; Finding a Generative Design Process Based on Biological Rules. *Session 13: Generative Systems - eCAADe 23*, pp.599-607.
- Gruber, P., 2011. *Biomimetics in Architecture: Architecture of Life and Buildings*. Wien: Springer-Verlag.
- Hensel, M. and Menges, A., 2009. The heterogeneous space of morpho-ecologies. In: M. Hensel, C. Hight and A. Menges, eds. 2009. *Space Reader: Heterogeneous Space in Architecture*. United Kingdom: John Wiley & Sons Ltd., p.208.
- Janssen, J.J.A., 1991. *Mechanical Properties of Bamboo*. New York: Springer-Verlag.
- Khosrow, G., 2005. Bamboo as Reinforcement in Structural Concrete Elements. *Cement and Concrete Composites*, No. 27, pp.637-649.
- McMahon, T., 1973. Size and Shape in Biology. *Science, New Series*, Vol. 179, No. 4079, pp.1201-1204.
- Otto, F. and Rasch, B., 1996. *Finding Form: Towards an Architecture of the Minimal*. Germany: Edition Axel Menges.
- Otto, F., 1971. *Biology and Building: Part 1*. Germany: Universitat Stuttgart.
- Sarkisian, M., Long, E., Doo C.S. and Shook, D., 2011. Learning from Nature. *Civil Engineering-ASCE*, Vol. 81, No. 6, pp.60-65.
- Sarkisian, M., Lee, P., Long, E. and Shook, D., 2010. Organic and Natural Forms in Building Design. *ASCE/SEI 2010 Structures Congress*, Orlando, Florida.
- Vincent, J., 2001. Stealing ideas from nature. In: S. Pellegrino, ed. 2001. *Deployable Structures*. Wien, New York: Springer-Verlag, pp.51-58.
- West, G.B. and Brown, J.H., 2004. Life's Universal Scaling Laws. *Physics Today*, 57(9), pp.36-42.