# Biomimetic Strategies in Tower Design

## *Towards the integration of tower subsystems*

*Elif Erdine*
*Architectural Association (AA) School of Architecture*
*http://www.elif-erdine.com*
*elif.erdine@aaschool.ac.uk*

**Abstract.** *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.*
**Keywords.** *Tower; biomimetics; integration; differentiation; generative algorithms.*

## INTRODUCTION

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.

"Biomimetic Strategies in Tower Design: Towards the Integration of Tower Subsystems" is an ongoing PhD thesis being conducted at the Architectural Association (AA) PhD in Architectural Design Pro-

gramme. The research 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 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 wind stresses.

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 (2007), based on the first classification proposed by Khan. Accordingly, structural systems for tall buildings can be divided into two categories according to the location where their lateral load resisting system is concentrated: interior structures and exterior structures.

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, each distinct tower system has a homogeneous 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.

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, it can be stated that tower structural system has developed with single objective optimization. The current organization of the tower subsystems, which are classified into five groups as the structural skeleton, floor slabs, circulation system, envelope, and environmental systems, have developed in an independent manner with regards to their internal material organization. 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 can influence the spatial configuration of other sub-

systems. This additive approach, where each subsystem is considered as a separate layer, results in the inefficient and excessive planning of tower material organization. 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 additional capacity has not been exploited such that it can become a fully integrated part of the primary subsystem. 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 existing systems which are capable of integration and co-adaptation.

## BIOLOGICAL ANALOGIES

### *Branching Structures*

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 and Rasch, 1996).

Methods of transmitting forces over a given distance in the most effective way have been explored by Frei Otto and his team. 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 transmission 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 transmitted on the shortest possible path, but the overall path length increases drastically. The third method, namely the minimal detours system, can be viewed as a negotiation between the minimal path and the direct path systems. 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. 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 (Figure 1) (Otto and Rasch, 1996).

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 and Rasch, 1996).

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 continuous between different subsystems of the tower, such as between the vertical members of the primary structure and the horizontal members of floor slabs. As such, a hierarchical design system can be proposed where branching logic can serve to facilitate material organization in the most effective way.

### *Bamboo Stem*

Bamboo stem is formed of long cellulose fibers embedded in a ligneous matrix. The fiber distribution along the stem is differentiated along the height; 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 (Khosrow,

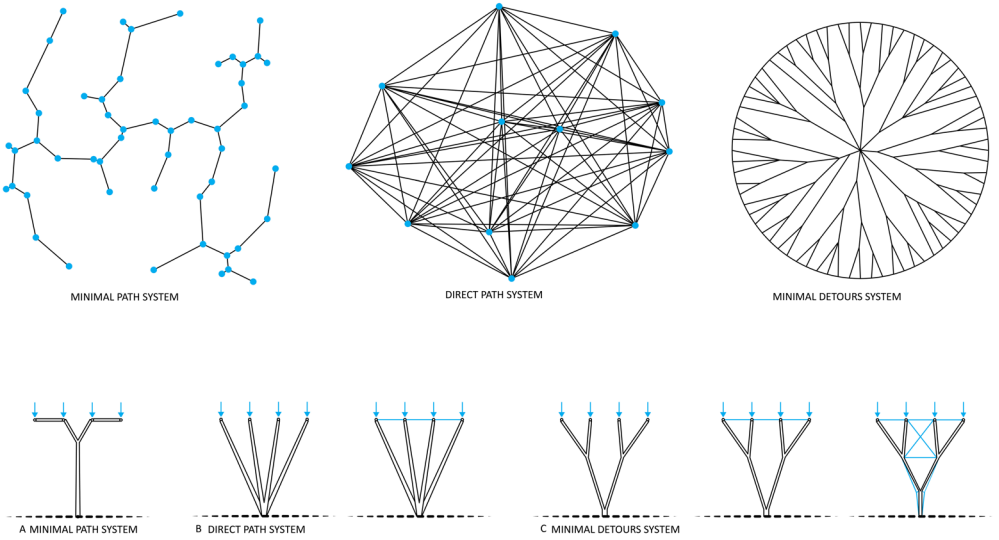



*Figure 1*
*Branching Constructions.*

2005). 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 is comprised of 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 (Figure 2). 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, Lee, Long, and Shook, 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 (1991). The equations below summarize the correlations which can be observed in many bamboo species (Sarkisian et al., 2010):

Internode Number: $x_n = n^* 100/N$ (1)

Internode Length: $y_{n1} = 25.13+ 4.8080x_n – (0.0774x_n)^2$ (below mid-height) (2)

$y_{n2} =178.84- 2.3927x_n + (0.0068x_n)^2$ (above mid-height) (3)

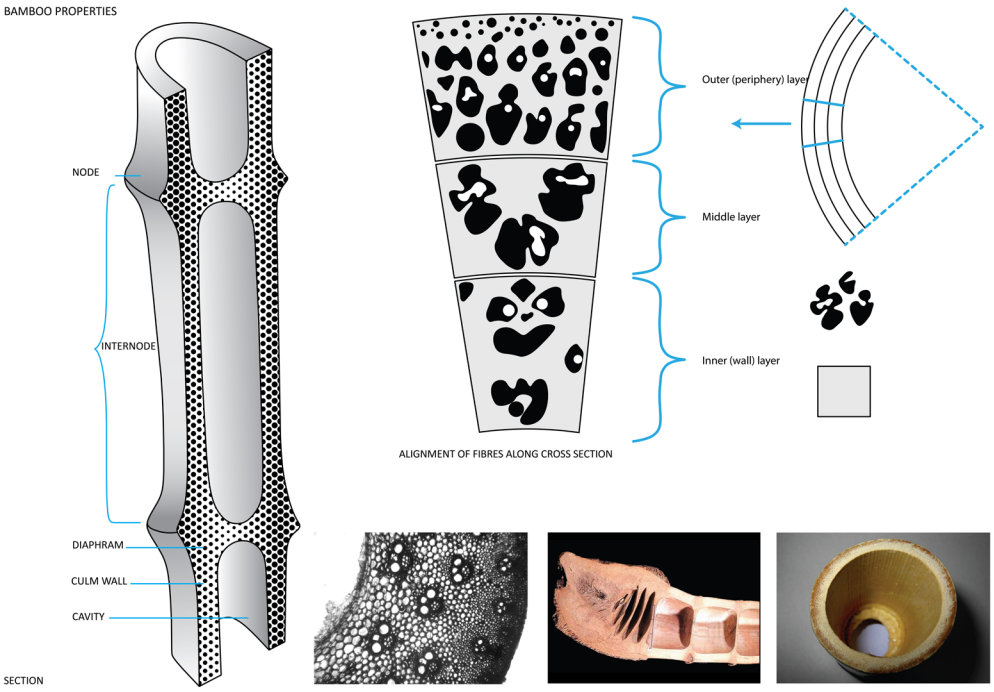
Internode Diameter: $d_{n1} = 97.5 - 0.212x_n + (0.016x_n)^2$ (below mid-height) (4)

$d_{n2} =178.84- 2.3927x_n + (0.0068x_n)^2$ (above mid-height) (5)

Wall Thickness: $t = 35 + 0.0181(x_n - 35)^{1.9}$ (6)

In these equations, $x_n$ is the internode number, *n* is a shaping parameter; *N* is the height of the structure; yn 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

*Figure 2*
*Bamboo Stem Properties.*




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, enabling higher 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 et al., 2010).

The morphological relationships of bamboo stem can be 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 vertical position and diameter 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, 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 loading condition.

## 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

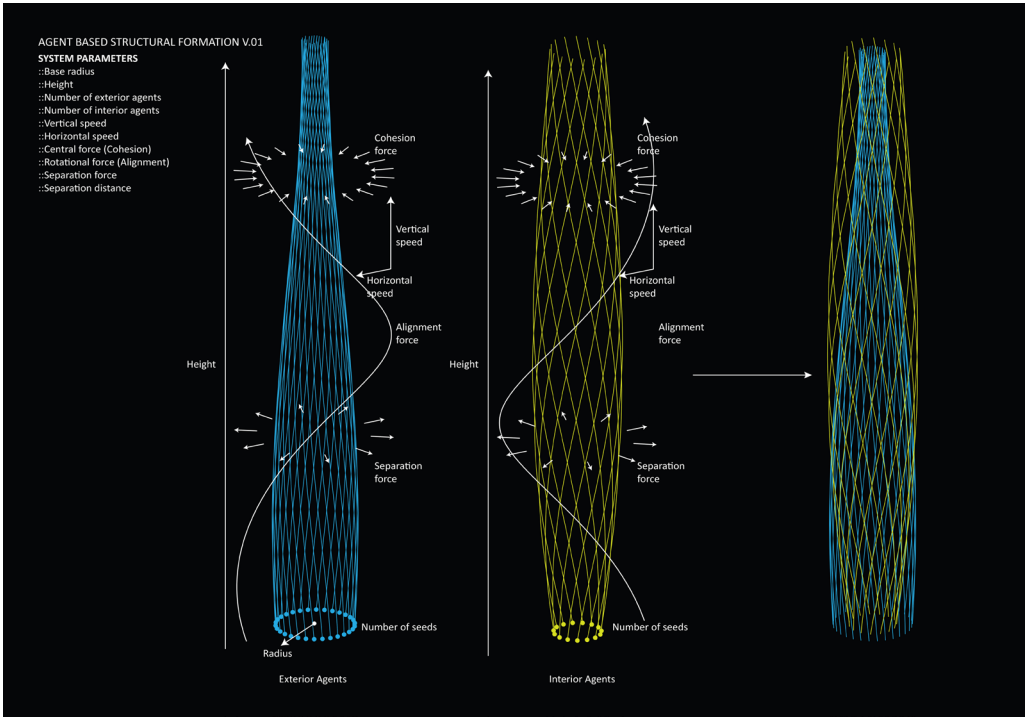
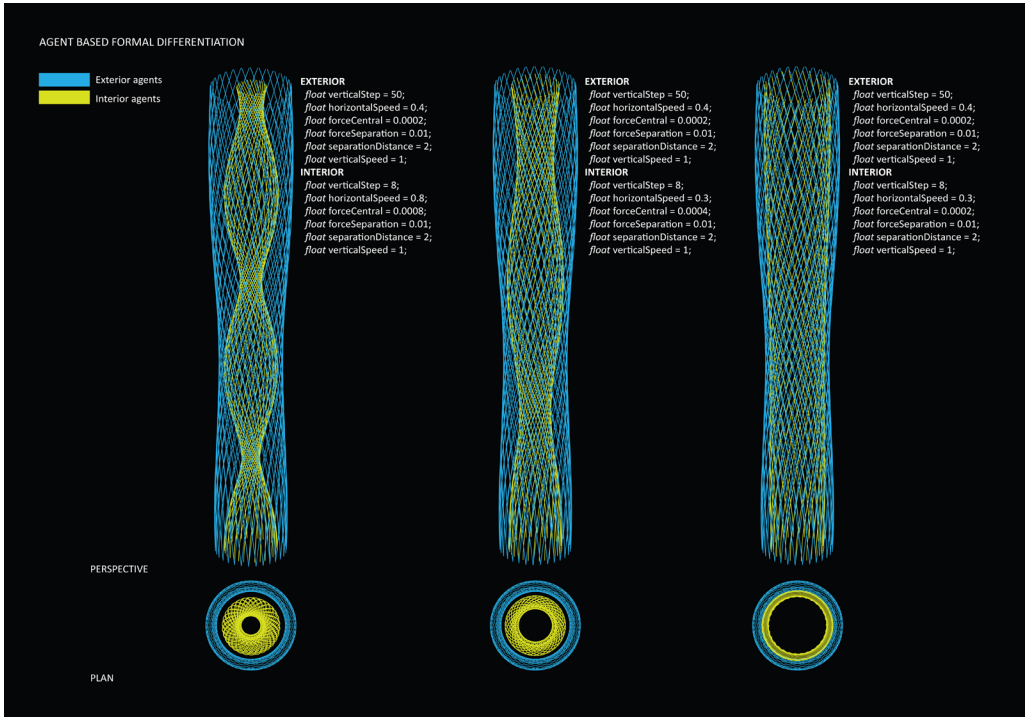



*Figure 3*
*Agent-based structural formation model.*

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 (Figure 3).

*Figure 4*
*Agent-based formal differentiation.*




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 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 (Figure 4).

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 (Figure 5). 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

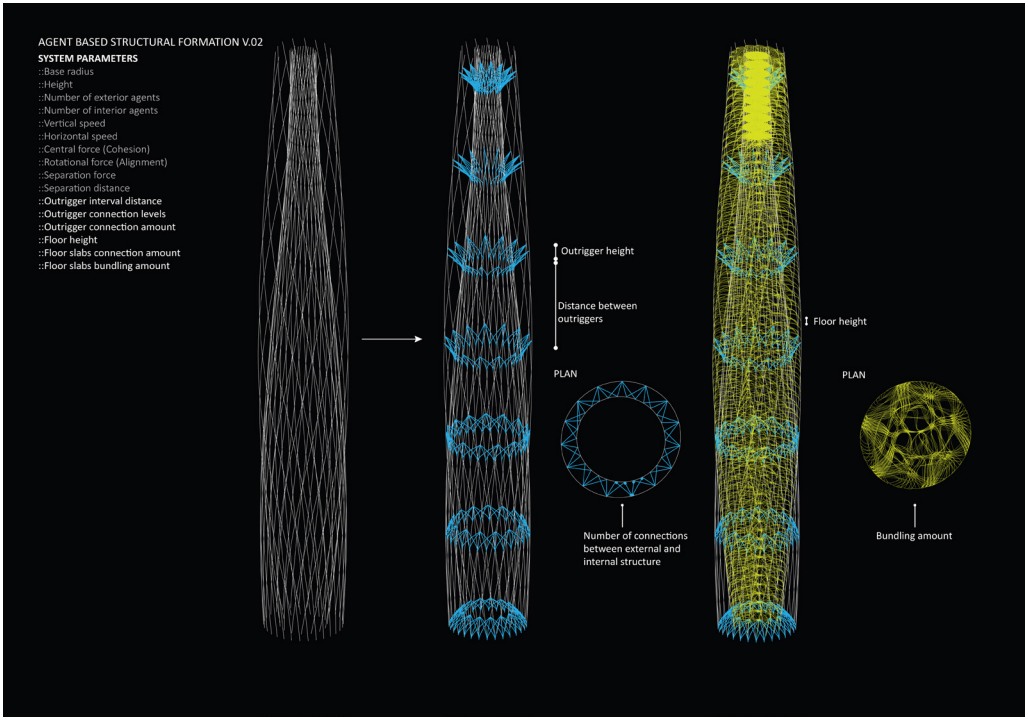



*Figure 5*
*Generation of outrigger system and floor plates.*

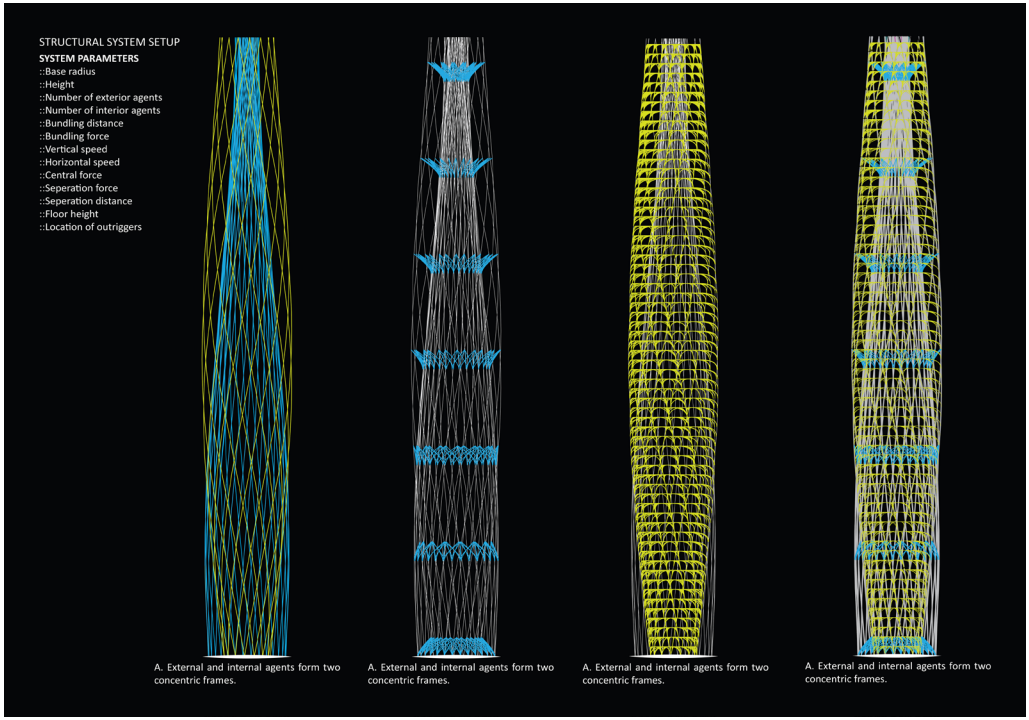
shift from the traditional method of relying on a rigid internal core and a series of columns for stability (Figure 6).

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 travelling 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.

## CONCLUSION

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

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




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 aims to bring

out new forms of design knowledge in the area of tower research by merging architecture, biology, and computation.

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