ABSTRACT
The research presented aims to develop a generative system of design which offers simultaneous integration and differentiation throughout the subsystems of a concept for a tall building during the conceptual design phase. The tower subsystems are classified into five groups as the load-bearing structure, floor system, vertical circulation system, façade, and environmental system. The aspects of multi-functionality and co-adaptation are articulated through the investigation of specific biological models in nature. The biomimetic analogies are the mechanical and organizational properties of branched constructions, the mechanical properties of the bamboo stem, and the microstructure of the porcupine quill/ hedgehog spine. The main motive behind selecting these natural structures is their shared property of increasing buckling resistance against environmental factors by self-organizing their material arrangement via certain geometrical rules. Moreover, the quality of multi-functionality is observed through the achievement of geometrical differentiation to the same material organization across vertical and horizontal axes. The methodology formulated by design parameters lays the foundations for a new integration approach, termed as multi-parameter integration, where the focus is set on the convergence of multiple design parameters simultaneously. Design explorations are carried out in the open-source programming language Processing via real-time generative form-finding techniques. Biomimetic analogies formulate the principals of geometrical behaviour mechanisms which, together with motion behaviour mechanisms, establish the geometrical parameters of the devised methodology. Geometrical behaviour mechanisms are inscribed in the data structure of various agent systems, each of which is responsible for generating a tower subsystem. The output model combines key properties of the biomimetic principles with geometrical and mathematical descriptions in order to devise a differentiated tower formation where the discrete subsystems behave in an inter-dependent manner.
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. In contemporary urban conditions, 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.

The research presented in this paper formulates part of the methodological approach of a recently completed PhD thesis. It is witnessed that the high level of complexity encountered in the initial phase of tower design is not managed in its entirety by establishing connections between multiple design parameters which have the potential to control the performance of all tower subsystems, revealing that presently there is partial integration of tower subsystems during the conceptual design phase. The tower is selected as the building type for research, since from an architectural and engineering point of view, building form, vertical circulation, and building systems function very differently in a tall building than low-rise buildings. The realization of efficient net-to-gross area ratios, the response of structure against lateral loads, the environmental regulation of interior areas, vertical circulation, and the tall building’s impact on its surroundings are some of the most critical aspects of a tall building which differ to other building types. As such, the research focuses on the incorporation of the functional parameters of the tower system with principles of biological models in order to propose computationally generated dynamic systems for the tower typology. The principle aim is to achieve simultaneous integration of tower subsystems which can coherently adapt to their internal and external context during the initial phases of the design process. In this framework, the tower subsystems are grouped as the structural system, floor system, vertical circulation system, façade system, and environmental system.

The paper focuses on the implementation of the specific biomimetic analogies towards the integration of tower subsystems through computationally generated dynamic systems. The biomimetic analogies are the mechanical and organizational properties of branched constructions, the mechanical properties of the bamboo stem, and the microstructure of the porcupine quill/hedgehog spine. The main motive behind selecting these natural structures is their shared property of increasing buckling resistance against environmental factors by self-organizing their material arrangement via certain geometrical rules. Moreover, the quality of multi-functionality is observed through the achievement of geometrical differentiation to the same material organization across vertical and horizontal axes.

Figure 1
Diagrams showing the direct path system, minimal path system and minimal detour system respectively. Figure created by author from data by Otto, Rasch and Schanz 2006, p. 47, 70.
BIOMIMETIC PRECEDENTS

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, Rasch and Schanz 2006, p. 158).

Methods of transmitting forces over a given distance in the most effective way have been explored by Frei Otto and his team (Figure 1). 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. 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. As a result, branched structures generated with minimal detours system use less material in a more effective manner (Figure 2) than the ones generated with direct path system (Otto, Rasch and Schanz 2006, p. 68).

Bamboo is a group of giant grasses formed of long cellulose fibres embedded in a ligninous matrix. The fibre distribution along the bamboo stem is differentiated along the height; the distribution of fibres 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 (Ghavami 2005). The phenomenon of differentiated distribution of fibres 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. 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 3). Moreover, 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 2010).

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

**Internode Number**

\[ x_n = n \times \frac{100}{N} \]

**Internode Length**

\[ y_{n1} = 25.13 + 4.8080x_n - (0.0774x_n)^2 \] (below mid-height)
\[ y_{n2} = 178.84 - 2.3927x_n + (0.0068x_n)^2 \] (above mid-height)

**Internode Diameter**

\[ d_{n1} = 97.5 - 0.212x_n + (0.016x_n)^2 \] (below mid-height)
\[ d_{n2} = 178.84 - 2.3927x_n + (0.0068x_n)^2 \] (above mid-height)

**Wall thickness**

\[ t = 35 + 0.0181(x_n - 35)^{1.9} \]

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 become shorter than the mid-height, increasing 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 2010).

Porcupine quills and hedgehog spines are essentially hair which is enlarged and stiffened for various purposes. Their difference lies in their functionality such that porcupine quills are mainly used for defense purposes while hedgehog spines operate as shock absorbers (Vincent 2002). In nature, assemblies with a cellular structure are found in abundance. Various tubular structures, such as plant stems, support their outer circular shell with a foam-like layer of parenchyma cells; in a similar fashion, porcupine quills, hedgehog spines, and bird feather quills too contain a layer of low density, foam-like cells in their interior volume (Figure 4). Being loaded primarily in bending and/or compression, the major purpose of internal cellular volumes is to act as an elastic support in order to enhance the resistance of the outer shells against kinking or local buckling without failing (Gibson 2005). These natural assemblies resist loads with the use of least

![Porcupine quill and hedgehog spine properties](image-url)
amount of materials possible, thereby suggesting that their anatomical and mechanical principles can be utilized for the improvement of mechanical efficiency in architectural constructs.

Various analyses carried forward about the mechanical performance of these different microstructures have shown that the core acts as an elastic foundation where the stresses are at a maximum on the shell-core interface, decaying inward in a radial manner. More specifically, calculations have been made in order to show how much the cellular core structure can stabilize the shell of the quill/spine against buckling when it is loaded on end as a strut. Porcupine quills perform similar to hollow tubes in buckling with an axial load, and in bending they are approximately 40% better. However, hedgehog spines, bearing longitudinal and radial stiffeners in a honey-comb fashion in their core, perform three times better than they would without the core, proving to be the most efficient microstructure (Vincent 2002, p. 31).

The combination of the properties of branching structures, bamboo stem, and porcupine quill/hedgehog spine can help to define a seamless fibrous tower formation where the discrete subsystems can be integrated across a range of scales, leading to the properties of multi-functionality, differentiation, and co-adaptation to emerge.

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**METHODOLOGY**

The developed methodology, termed as multi-parameter integration, employs real-time generative form-finding techniques, described as bottom-up processes where design output emerges from the interaction between autonomous agents and their environment in the Object-Oriented Programming environment, Processing. There are various principal rules and feedback mechanisms which operate across all the classes in the Processing algorithm. First of all, it must be stated that each of the five subsystems of the tower system is generated as one class or a cluster of classes. Figure 5 demonstrates the major geometrical and organizational behaviours of each subsystem in the Processing algorithm. The vertical circulation agent system, the interior structure agent system, and the exterior structure agent system are generated in the initiation of the code as independent classes. The circulation agent class then initiates the floor slab agent class, following a linear flow. The interior and exterior structure agent classes together initiate the outrigger agent class as well as the interstitial slab agent class. As the exterior and interior structure agent classes are activated independently from each other, the outrigger agent class and the interstitial slab agent class are formed as a result of the feedback relation between the exterior and interior structure agent classes. The exterior structure class initiates the façade agent class. The linear and feedback associations between various classes are further illustrated in (Figure 5).

The major purpose of the methodological approach is to converge multiple design parameters simultaneously and expose the level of complexity in tower subsystem
integration from the outset of the design process. Initially, various design parameters obtained from previous research on current tower subsystems and selected biomimetic examples are grouped into functional parameters, geometrical parameters, and topological parameters so that the focus is on convergence and integration. Design parameters are integrated with a hierarchical approach where interdependencies across multiple tower subsystems arise on a multitude of levels. Figure 6 portrays the complete set of tower subsystems generated via the Processing algorithm, while Figure 7 depicts the generation process of tower subsystems in a more close-up perspective.

In this research, the geometrical parameters are essentially formed by two mechanisms which work in a reciprocal manner, motion behaviour mechanisms and geometrical behaviour mechanisms. Motion behaviour mechanisms are based on the steering behaviour of autonomous agent groups. The steering behaviour gives the ability to control the motion of agents based on separation, cohesion, and alignment rules. According to the changes in the weights of these parameters, a certain degree of design freedom can be achieved in manipulating the motion behaviour of the agents. The motion behaviour of the agent can be coupled with geometrical behaviours, creating the foundations for real-time generative form-finding techniques. As such, it is crucial to explain how the geometrical attributes of the selected biomimetic analogies are implemented in order to meet the challenge of the design problem.
Branching organizations are applied on the tower context in various ways. Firstly, due to their structural efficiency, they are implemented to the structural members of the load-bearing system (Figure 8). The organization of the structural members are defined in relation to the mathematical rules of minimal detours systems in order to resist the loading conditions of the tower in the most effective way (Figure 9). Moreover, due to their material efficiency, minimal detours systems rules are embedded in the geometrical organization of all the tower subsystems. As branched constructions have a hierarchical geometrical order, they serve as a medium for spatial differentiation. An example of this condition is utilizing minimal detours system for the differentiation of façade elements in relation to the distribution of exterior structure elements (Figure 10). In effect, branching organizations can serve as a transition condition from one subsystem to another, creating a seamless geometrical connection between various subsystems.

The material organization of bamboo stems is applied to the load-bearing structural system of the tower on a global scale, whereby the diaphragms of the bamboo stem serve as an analogous model for an outrigger system in the tower. The position and the diameters of the outriggers are predicted by using the bamboo stem mathematical equations in order to resist lateral loading conditions in an effective manner (Figure 11). Moreover, the fiber concentration along the perimeter of the stem in order to supply resistance against buckling can serve as a geometrical model for the organization of the structural system. As such, the load-bearing structure can be organized as a double-layer structural system which is inter-connected on certain levels in order to generate a dense circumferential fibrous geometrical organization. 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. The double-layer structure is employed further as a double-skin façade that can have passive environmental benefits. In this way, openings in the double-skin façade and cavities in the interstitial space between the exterior and interior structure can be designed to improve natural ventilation throughout the tower. Habitable spaces are introduced in the interstitial areas in order to keep the percentage of usable space at a maximum level. Moreover, concentrating the structural elements along the entire perimeter of the tall building enables the positioning of service cores in an independent location, as long as the stability of the building is maintained.

The internal organization of porcupine quill and hedgehog spine microstructures has several implications for the geometrical configuration of tower subsystems. Firstly, the performance of the double-layer structural system, which is an outcome of the principles of the bamboo stem, can be enhanced by a network of stiffeners positioned in its interstitial space so that resistance against buckling is increased. In this manner, it can be observed how the bamboo stem and porcupine quill / hedgehog spine microstructures can begin to complement each other’s performance. The interstitial spaces of the double-layer structure can be habitable areas with different spatial qualities than the internal habitable areas (Figure 12). The floor systems of both the internal areas and
interstitial spaces can be generated according to branching rules, thereby extending the geometrical principles of the vertical structure along the horizontal axis (Figure 13). Similar to the microstructure of the porcupine quill / hedgehog spine, the internal spatial layout of the tower can have a radial arrangement in order to improve the resistance of the double-layer exterior structure against buckling. A radial plan form can also be advantageous in order to respond in a uniform manner against the various environmental forces surrounding and acting upon the tower.

The motion behavior mechanisms and geometrical behavior mechanisms work in a complementary mode. While the motion of the group of autonomous agents is controlled by steering behaviour with a limited degree of freedom, the mathematical description of branching organizations, of bamboo stem cross-section, and of porcupine quill / hedgehog spine are embedded in the motion behaviour, generating higher control in the overall behaviour of the group of autonomous agents. Furthermore, limited degree of freedom can be sustained in this setup by designating certain parameters for each biomimetic model, adding to the parameters of separation, cohesion, and alignment which solely guide steering behaviour. In effect, the emergence of complex behaviour in real-time generative form-finding procedures can be stimulated by changing the weights of all the parameters (Figure 14).

In this respect, it is crucial to summarize how the subsystems are inter-dependent on each other while at the same time exhibiting multi-functionality as an inherent quality. The outrigger system and interstitial slabs serve to connect the exterior and interior structural systems while the floor slabs are tied to the interior structure and vertical circulation system. Meanwhile, the façade system supports the exterior structure, as its lateral members connect the vertical members of the exterior structure. As the double-layer structure, vertical circulation system, and façade system act in compression, the floor slabs, outriggers, and interstitial slabs act in tension. Thus, the floor slabs, outriggers, and interstitial slabs prevent the double-layer structure, vertical circulation members, and façade from collapsing while the double-layer structure, vertical circulation members, and façade, in turn, support these lateral members. As such, the distribution of loads takes place over the entire fibrous members of the tower in a seamless fashion, presenting a significant shift from the traditional method of relying on a rigid interior core and a series of columns for stability (Figure 15).

**CONCLUSIONS**

The unifying features which branching structures, bamboo stem, and porcupine quill / hedgehog spine share are their ability to increase their buckling resistance by self-organizing their material arrangement through geometrical rules which aid in the stiffening of these formations against external factors. As such, an important lesson to learn from biology is that nature folds various functions into basic material systems through differentiation. The systematic diversity in the observed and microscopic world of nature
occurs due to the ways in which these basic materials re-order and self-organize themselves to form such constructions. Diversity in nature does not emerge from which materials to use, but how to use available materials (Hensel and Menges 2010, p. 15). In effect, the aspect of ‘how’ puts forward the significance of geometrical rules with respect to self-organization and differentiation once again. The genetic code of the biological structure bears information for the self-organization of its form in relation to the environment, pointing to the fact that the processes necessary for the material organizations to carry on distinct functions at once, such as structure, transportation, storage properties, are encoded in the DNA itself.

In a similar fashion, the level of complexity that architecture possesses can be utilized from the outset of the design process in order to establish qualities of multi-functionality and co-adaptation. As architectural constructions cannot have prescribed genetic codes or instructions, it is up to the designer to envision and generate creations of architecture as complex systems with inherent adaptability and heterogeneity properties. By achieving the seamless flow between geometrical hierarchies and related functions, architectural formations can carry on distinct functions at once. In this respect, it is important to note that the generative nature of the chosen methodological approach shifts the focus of design explorations away from the end result towards the process of formation. This condition redefines the role of the architect away from getting involved with creating an end product according to rules/parameters, towards becoming the system designer whose task is to observe the outcomes of the system as it is continuously adapted on a multitude of interdependent levels. As the system designer, the architect curates the design processes with an intuitive notion of expected outcomes while employing scientific methods for architectural outputs. In the context of this research, it is acknowledged from the beginning of design explorations that the developed algorithm yields fibrous formations with a specific slenderness ratio, plan form, location of service cores, floor height, and overall height, which are parameters defined in the initial setup of the algorithm. Meanwhile, motion behaviour mechanisms, geometrical behaviour mechanisms, and topological associations, all of which are defined by parameters in the agents’ data structure, govern the generation of differentiated global patterns which could not have been predicted at the outset of design explorations.

While the research does not concentrate on aspects of detailed design development, practicality, affordability, effectiveness, fabrication, and assembly processes, it does present methods of achieving multi-parameter integration within a carefully selected set of subsystems by a collection of design parameters. In this process, it is necessary that the characteristics of each subsystem, hence the design parameters, are simplified for the purpose of testing integration methods. As such, it should be noted that the research does not aim to address the repercussions of all design parameters in an elaborate manner at this stage; rather it aspires to introduce the notion of integration into conceptual design phase and outline the key areas which need to be investigated in order to achieve tower subsystems integration.
The output model is characterized as a fibrous formation with a certain level of redundancy. The condition of redundancy is viewed as a positive feature rather than a disadvantage, since one of the key mechanisms observed in natural structures is the trait of robustness as an outcome of redundancy. In nature, redundancy is a strategy for supplying additional capacity in order to enhance performance and adaptation to environmental conditions, leading to the robustness of the organism (Weinstock 2006). As such, in contrast to the conventional method of engineering efficient solutions with a limited quantity of materials chosen for specific functions, it is argued that multi-parameter integration can lead to the emergence of multi-functionality, differentiation, and co-adaptation throughout the tower system due to its inherent qualities of redundancy and robustness.

The biological analogous models which have been explored can serve as unique models in the generation of "topological variation" throughout the height and circumference of a singular subsystem. Moreover, these models contribute to the distribution of the forces travelling throughout the tower according to multiple criteria, enabling the "inter-system differentiation" taking place between multiple tower subsystems owing to their inherent geometrical and material organizations. By manipulating the parameters of the algorithm, the performance of the tower in relation to structure, daylighting, orientation, ventilation, and floor efficiency can be fine-tuned on a local level. While each subsystem is manipulated by attributes and methods which are inscribed inside the agent systems' data structure, geometrical integration leading to performance-based integration, with differentiation and co-adaptation qualities, can be achieved. As such, form-finding through biomimetic analogies can move away from acting as single objective optimization and progress towards becoming a multi-parameter integration tool due to their coexisting structural and spatial attributes.
REFERENCES
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