Hyper-Morphology

Experimentations with bio-inspired design processes for adaptive spatial re-use

Nimish Biloria[1], Jia-Rey Chang[2]
HyperBody Lab, TU Delft
[1]http://www.hyperbody.nl/, [2]http://pandalabccc.blogspot.com/
[1]N.M.Biloria@tudelft.nl, [2]J.R.Chang@tudelft.nl

Abstract. *Hyper-Morphology is an on-going research outlining a bottom-up evolutionary design process based on autonomous cellular building components. The research interfaces critical operational traits of the natural world (Evolutionary Development Biology, Embryology and Cellular Differentiation) with Evolutionary Computational techniques driven design methodologies. In the Hyper-Morphology research, genetic sequences are considered as sets of locally coded relational associations between multiple factors such as the amount of components, material based constraints, and geometric adaptation/degrees of freedom based adaptation abilities etc, which are embedded autonomously within each HyperCell component. Collective intelligence driven decision-making processes are intrinsic to the Hyper-Morphology logic for intelligently operating with autonomous componential systems (akin to swarm systems). This subsequently results in user and activity centric global morphology generation in real-time. Practically, the Hyper-Morphology research focuses on a 24/7 economy loop wherein real-time adaptive spatial usage interfaces with contemporary culture of flexible living within spatial constraints in a rapidly urbanizing world.*
Keywords. *Evo-devo; cellular differentiation; self-organization; evolutionary computation; adaptive architecture.*

INTRODUCTION

Contemporary architecture and its growing fascination with the ingenuity of formal explorations supported by the increasing sophistication of computer aided design software comes with its own pros and cons. The growing importance of formal aesthetic has been misused and misinterpreted under the banner of organic and bio-inspired architecture, wherein mimicking of formal attributes has taken center stage. Computational design and its facets such as evolutionary computing, on the other hand are also gaining importance within academia as well as are percolating into some contemporary design offices wherein a distinction between top-down aesthetic visions as opposed to bottom-up simulation driven analytical form finding are being seriously questioned. Such explorations have been heavily instrumental in exploring biological processes of adaptation, growth and mutation, or in other words are truly concerned with understanding biotic principles and optimization phenomenon in order to derive performative design solutions. The desire to imitate organic form as opposed to understanding inherent biotic processes as bottom-up systemic interactions resulting in outward appearances unreservedly needs definite persuasion within the architectural domain. The research paper outlines one such approach of deciphering and translating the logics of natural morphogenesis into the digital realm and applying it to an architectural case of real-time adaptive re-use of space: Hyper-Morphology.

Hyper-Morphology outlines a bio-inspired evolutionary design process with a primary focus on cellular differentiation, adaptation and self-organization via collective decision-making processes. The research thus has its roots in the science of Evolutionary Developmental Biology (Evo-Devo), Embryology and Cellular Biology, which exemplify various stages of embryonic growth, cellular behavior and development cycles of an organism. In doing so, our research revealed the following critical traits within the natural world as quintessential:

- Regulation of cellular differentiation: Each specialized cell type in an organism expresses a subset of all the genes that constitute the genome of that species. Each cell type is defined by its particular pattern of regulated gene expression: the process by which information from a gene is used in the synthesis of a functional gene product. Gene regulation gives the cell control over structure and function, and is the basis for cellular differentiation, morphogenesis and the versatility and adaptability of any organism. At a local level, Signal Induction, which refers to cascades of signaling events, during which a cell or tissue signals to another cell or tissue to influence its developmental fate is equally important from a collective decision making point of view.
- Self-organization: In biological systems self-organization is a process in which pattern at the global level of a system emerges solely from numerous interactions among the lower-level components of the system. Moreover, the rules specifying interactions among the system's components are executed using only local information, without reference to the global pattern (Camazine, 2003).

Existing architectural spaces and their inherent static nature owing to their material make-up as well as the nature of linear processes, which lead towards their conception, are unable to provide the much needed flexibility as regards functional diversity, user-driven customization of space as well as adaptation within a dynamic context. Hyper- Morphology challenges such linear, non-dynamic processes and by means of inculcating built-in adaptive behavior within the smallest constituting component of architectural space (the cell) intends to make a transition towards understanding architecture as a performance driven, real-time adaptive construct. The ongoing research builds on the aforementioned critical traits in the natural world and will illustrate intricate, yet energy efficient information frameworks and communication protocols amongst autonomous cellular building components. The paper will also elaborate upon a simulation driven design interface (for intuitive communication with designers) as a front end to such non-linear computational process. The research also focuses on the applicability and thus the performance measurement aspects of such collective intelligence driven spatial systems within the context of real-time adaptive re-use of architectural space. Cellular differentiation/specialization is thus seen as a resultant impact of the gene expression within the inherent genetic code via intelligent communication capabilities based negotiation between all the architectural components.

THEORETICAL BACKGROUND

"What we are evolving are the rules for generating form, rather than the forms themselves" - John Frazer (1995) in his article "A Natural Model for Architecture". The research heavily draws on John Frazer's viewpoint and focuses on evolutionary growth and the role of DNA from a design process perspective in order to generate performance driven adaptive

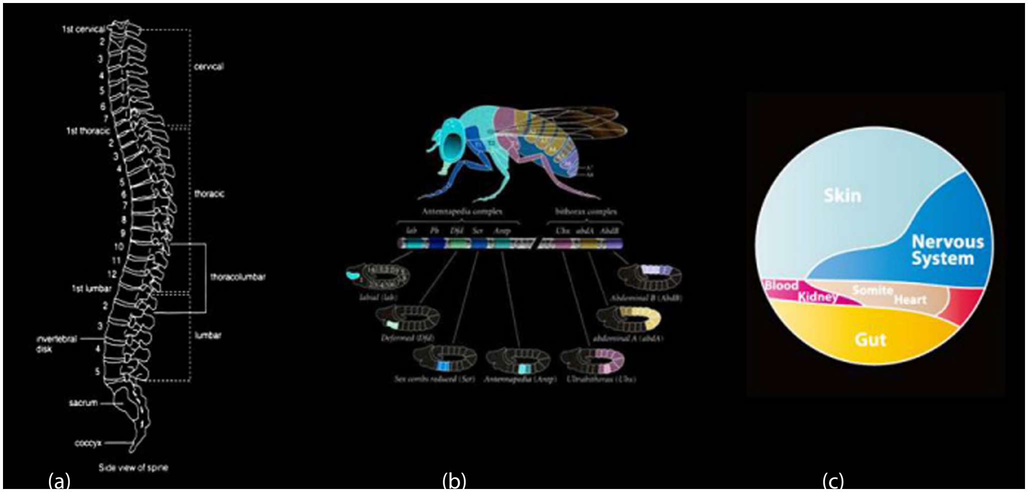


Figure 1
a) Vertebral Column, an expression of the Simple to Complex logic within Evo-Devo (image is from: http://creationwiki.org/Vertebrate). b) The Switch and Triggers of Hox-gene controls different parts of the Drosophila's morphology (image is from: http://www.dls.ym.edu.tw/lesson3/dros.htm). c) The "Fate Map" of embryo which drives the formation of the organisms (drawn by the author).

spatial solution sets. The research thus thoroughly explores Evolutionary Development Biology (Evo-Devo) to understand how organisms form from the differences of embryos and how the invisible logic inside the genes controls an organism's growth. The Hyper-Morphology research extracts three distinct ideas, which can be applied to architectural design from the field of Evo-Devo: "simple-complexity", "switch and trigger" and "geometric rules".

- The simple to complex logic can easily be discovered while studying an organism's body parts, such as the vertebrate's spine structure. Each complex organic body is composed of numerous amounts of simple elements with variations in scalar aspects of the same component (Figure 1a).
- The switch and trigger, on/off logics, play an important role in regulating the formation of the organism. For example, the switches inside the Hox gene tell an organism where and when to evolve different body parts in time. The characteristic of the output (form, color, pattern etc) is the resultant of multiple nested sets of inputs by these switches (Figure 1b).
- The geometric rules are mainly related to a "Fate-Map" during the embryo formation. Based on Sean B. Carroll's (2005) explanation in his book "Endless form most beautiful", A "Fate-Map" demarcates different functional areas of an embryo, which works as an information protocol for cells as regards the kind of cellular differentiation and specialization tasks they need to undertake (Figure 1c)

These fundamental logics together with the gene regulation processes give cells control over their structural and functional roles, thus defining cellular behavior and adaptation principles. This knowledge can in turn be applied to autonomous architectural components with the assistance of computational design routines. It has also been observed that genetic processes and evolutionary strategies in natural systems are easily misunderstood and misused by designers. Geometric form-finding processes are at times deduced by considering a DNA code as a metaphor for fixed formal attributes while completely ignoring the deeper relational processes that exists between encoded genetic information and the resultant phenotype. The research categorically opposes the much-simplified literal translation of A-C-T-G sequences within the DNA into the datasets of spatial vertexes, edges, transformation factors, and other geometric rela-

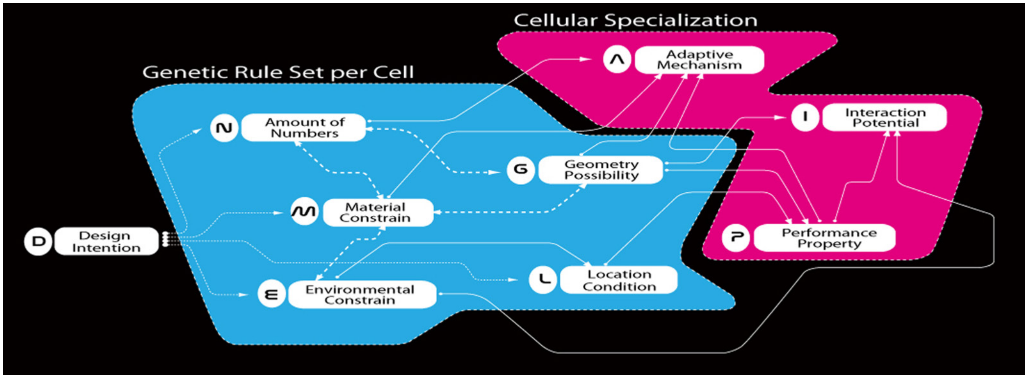


Figure 2
Diagram of genetic rule set per cell and cellular specialization in evolutionary design processes.

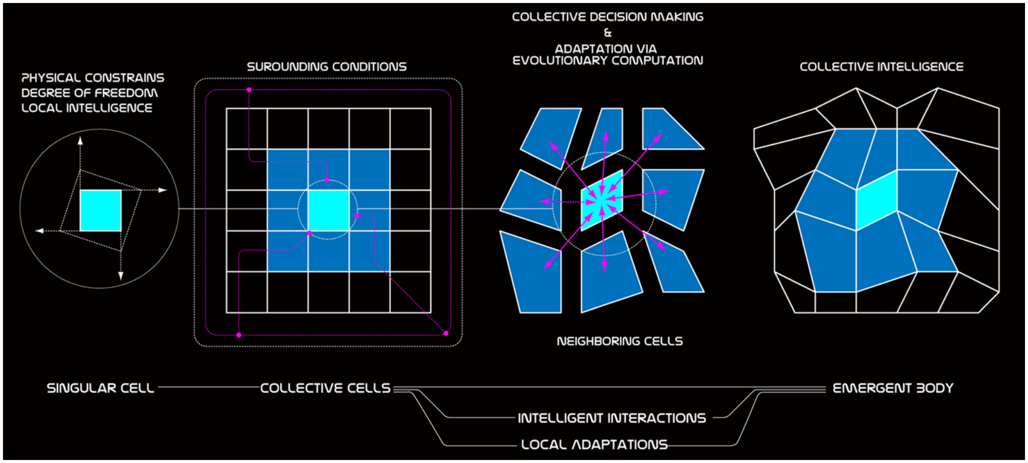
tionships for deriving a shape. On the contrary the research premise establishes that all genes in cells should unavoidably interact with each other as a relational system in a non-linear process in order to successively grow an organism from cellular differentiation and specialization based tissue formations into a holistic body. This necessitates a systemic relationship between genes as a vital area of research in order to extract rules for generating information driven performative form. In other words, the paper proclaims that designers should build bottom-up spatial formations by setting up genetic rule sets within the design process. These will be inherited within the smallest unit of the proposed space; the spatial component (similar to the cells in organisms). The number of such cells, their material make-up, their communication protocols and data exchange routines (gene expression and signal processing) while interacting with their immediate context in order to arrive at individual cell specialization (in terms of form and ambient characteristics) result in the generation of emergent morphological phenotypes (Figure 2).

TECHNICAL INTERPRETATION & ADAPTIVE USER-CENTRIC INNOVATION

Computational processes, which operate as a medium for translating biotic principles into spatial, mechanical as well as informational frameworks, take center-stage within the research. The focus here is also on bottom-up evolutionary computing processes rather than conventional top-down aesthetics driven solution-finding procedures, thus enabling one to seek parametric variations while assessing performance of the variants in real-time. Evolutionary computation (EC), a terminology widely used in the field of computational Intelligence explicitly deals with the creation of well-defined models (which can be expressed in an algorithm, protocol, network topology, etc.) pertaining to the understanding of evolution, which, in Biology is the process of change in the inherited traits of a population of organisms from one generation to the next. Architectural, Engineering and Urban design oriented research and design experiments via the EC perspective are thus seen as systematic attempts to understand and mimic how organic components and subsystems create nested processes with the ability to interact and adapt to their contextual dynamics in real-time.

Architectural design in the computational domain has heavily experimented on the idea of self-organization to see how micro-scale organic components and systems can create nested processes with the abilities to adapt to their dynamic context in real-time. The research emphasizes swarm intelligence as a self-organizational computation strategy under the umbrella of Evolutionary Computation. Numerous autonomous components (HyperCell) with material limitation driven local degrees of free-

Figure 3
Process of collective decision making through local level adaptive components to emergent optimized body for the information distribution idea within the logic of self-organization and swarm intelligence.



dom akin to cells in an organism thus create the foundation of collective decision-making scenarios in this research (Figure 3). Based on local adaptation routines stored within each component's DNA, efficient negotiation scenarios between immediate neighboring components are structured in order to collectively decipher performative morphologies in accordance with user requirements as regards the activities they wish to perform. This collective decision making scenario applies to diverse set-up of the components with differing material and geometric make-up in the form of variable gene regulations akin to cellular differentiation mechanisms in the natural world.

Instead of having a central core for distributing data from and to the components, the idea of data transmission in this research involves embedding each single component with a low-level processor, which computes local adaptation routines and generates protocols for communicating with its neighbours on the fly in an energy efficient distributed information processing architecture. This distribution process is similar to Signal Induction in natural growth processes, which refers to cascades of signaling events in order to provoke cell's to send signals to their neighboring cells in an attempt to attain informed cellular differentiation.

The research does not only deal with the data exchange between cellular components, but also tries to establish an active communication between components, environment, and users in real-time. Charles Darwin once said, "It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is the most adaptable to change." Adaptation mechanisms play a crucial role for an organism to survive, sustain and grow. As opposed to a responsive system, which operates on a much linear communication process, the research thus harnesses an adaptive systemic logic involving real-time non-linear interactions with the immediate context and end users.

The user-centric nature of the HyperCell implies real-time structural, physiological and ambient adaptations for optimal end-use. This involves consideration of user's activity oriented needs, issues of human computer interaction, and tangible or digital communication modes with the HyperCell components. In other words, the term user-centric refers to the user's possibilities of communicating; modifying and customizing the collective intelligence driven generated morphologies of HyperCell clusters. Towards this end, everyday digital gadgets such as smartphones, tablets, and multi-touchscreen devices, with intuitive user-interfaces will be utilized.

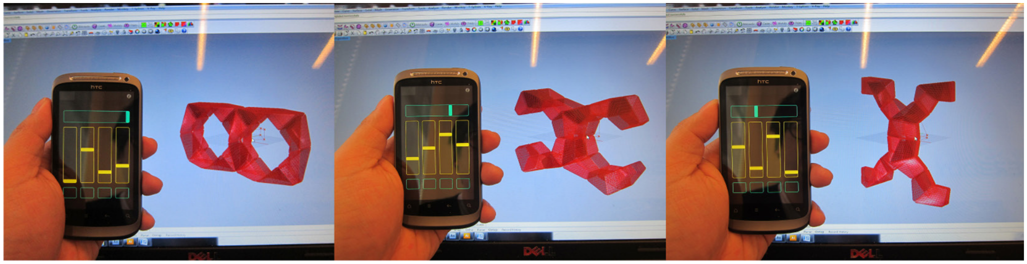


Figure 4
Experiment of controlling the visual 3D model through a smart phone device.

3D interaction gesture tools, such as Kinect by Windows, which control virtual objects by responding to user gestures, will also be extended to interact ubiquitously with physical HyperCells in real-time (Figure 4).

Considering this user-centric approach, the issue of Evolution in this research takes up the dimension of novel interactions produced by diverse combinations of HyperCells as well as topological and ambient customizations produced by end-users within a HyperCell cluster. The users in this manner explore and customize spatial topologies within a set technical adaptability range in order to self-create multiple usability scenarios.

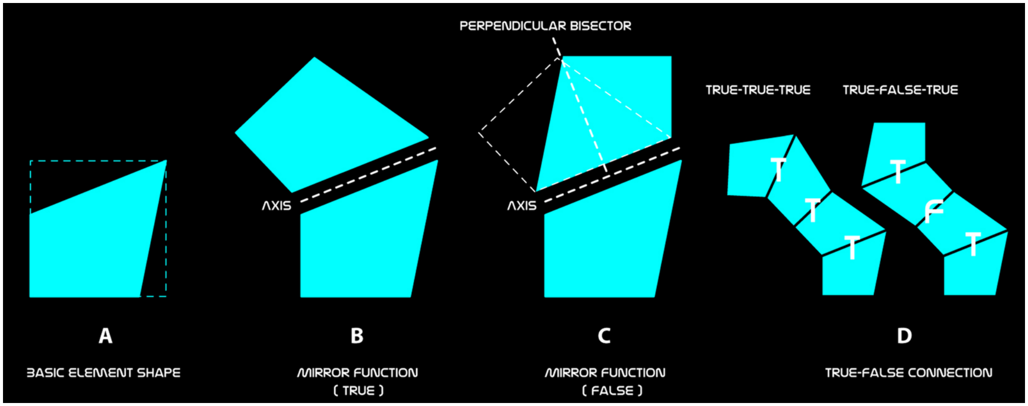
EXPERIMENTAL CASE STUDY

HyperCell as an autonomous architectural component system will be applied to an interior scale as the first experiment. Each HyperCell component has its own geometrical definition; a Hexahedral (cubic) geometry in this case, and will in real-time adapt and transform its geometrical shape in response to contextual factors and user based activity requirements to generate feasible topologies. Following the aforementioned theoretical logic and tangible techniques, the HyperMorphology research in this phase puts more focus on experimenting with diverse functional furniture morphologies harnessing the aforementioned number of cells and the combination logic of the HyperCells.

At the starting stage of the simulation process, the fundamental geometry, the transformation process and the communication logic are explored in parallel using computational techniques. The initial research phase employs a 2-dimensional quadrangle based structure as the fundamental element of the HyperCells. From a parametric point of view, the coordination and control of the constituting four vertices of a single quadrangle shape contributes towards attaining geometric variability and transformation possibilities to the HyperCells (Figure 5a) In other words, different lengths of a basic quadrangular element's edges define a repeated geometric shape in order to compose a singular HyperCell component by following the "mirror" geometric transformational function. The mirror function as a mathematical definition is called a reflection transformation based on a mirror (a line for 2D space or a plane for 3D space as an axis of reflection) to map a specific figure to its opposite position to create symmetry. In this research, two different mirror functions have been applied as "True and False" logic while composing the HyperCell component.

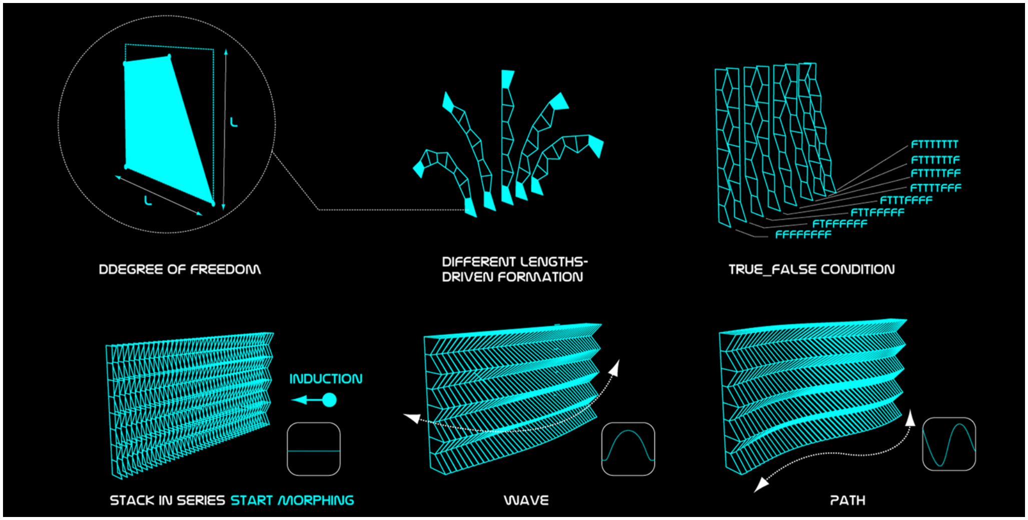
The "True mirror function" stays with the general reflection idea to create a symmetric figure based on one of the original quadrangle's edge (Figure 5b). The "False mirror function" adds one step after getting the reflected figure by the True mirror function. Instead of using the quadrangle's edge as an axis of reflection, the "False mirror function" makes another reflection based on the first reflected shape's perpendicular bisector (Figure 5c). This True and False combination logic is a crucial mechanism of forming a single HyperCell component by connecting the quadrangular cells together. This can be interfaced with the switch and trigger mechanism extracted from Evo-Devo: for example, if we connect four quadrangular cells as a basic HyperCell component, first we have to decide the True or False sequence, such as TTT or TFT (T = True and F = False) as con-

Figure 5
a) Degree of freedom in terms of dimensions. b) True mirror function. c) False mirror function. d) Example of True & False regulation between cells.



necting regulations between cells (Figure 5d). This simple regulation of True and False sets up the basic formation of the HyperCell component similar to the gene regulation process of living creatures, which defines their body parts. Besides this, the other critical logic involves that all basic quadrangle cells share the same dimension to build up a single HyperCell (Figure 6). Once a particular quadrangular cell gets its dimensional information from the system to change one of its edge's lengths, it will pass this information to its neighboring cells in order to do the same transformation so that the overall HyperCell components can make different bending formation in real time for different usages. This data transmission is related to the information distribution between cells. Furthermore, by extruding the 2D quadrangular cells of particular lengths as 3D-Hexahedral elements, the transformation mechanism can still be embedded and applied to build a 3D HyperCell component.

Figure 6
Diagram illustrating the various wall typology of the HyperCell from basic geometric element with the degree of freedom and simple rule-based logic.



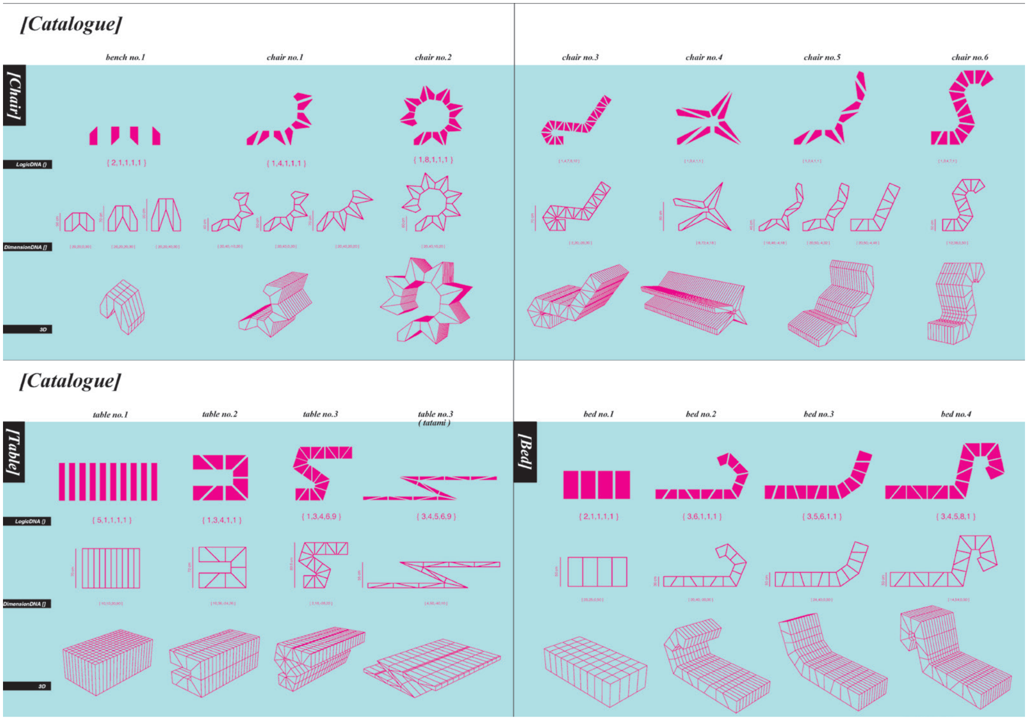


Figure 7
Part of the catalogue of the furniture pieces built up by the HyperCell components. First line of the diagram shows the Logic-DNA of how the HyperCells construct. Second line of the diagram represents the actual dimension of the furniture pieces.

The goal of using the same set of HyperCells with different combinations to create different furniture functions is to achieve all required spatial usages within the same foot print in real-time. With this goal, multi-functional HyperCells can, owing to their adaptation possibilities minimize each person's generic spatial volume for living. Two sets of parameters which are Dimension-DNA (D-DNA) and Logic-DNA (L-DNA) drive the main furniture (trans)formation built by HyperCells, such as chair, table, bed, etc. (Figure 7). These two sets of parameters are related to the transformation logics which were discussed earlier while defining the basic quadrangular shapes and the manner of connecting them. D-DNA defines the basic geometry to build up the overall furniture shape bottom-up, and the L-DNA defines the True and False mirror function between each cells' connections.

Apart from applying principles of cellular differentiation the idea that all species share the same gene tool-kit, involving simple operations to produce complex outcomes and attain morphological variation via simple switch and trigger mechanisms are perfectly experimented with in the research. Although all cells (HyperCells) share the same degree of freedom (D-DNA), but with different amount (number) and geometric regulations (L-DNA), they create various functional furniture formations to fulfill different spatial and usage based topological requirements. This on-going research subsequently aims to develop and market the HyperCells as flexible and transformable furniture pieces apt for adaptive reuse. In other words, a set of HyperCells bought by customers, can be assembled differently by using different D-DNA and L-DNA to attain specific furniture functions, or enable the embodiment of different transforming abilities to existing functions in order to suit the customer's spatial requirement in time as regards the active reuse of space (Figure 7). The research, after experimenting with HyperCell furniture systems will subsequently focus on how these autonomous objects can in real-time send data between each other under locally and how users can effortlessly communicate with them to customize spatial adaptations.

CONCLUSION

Unlike so-called organic architectural designs, which literally mimic natural organic shapes with the assistance of sophisticated computational techniques, the HyperMorphology research engages in deciphering and translating the logics of natural morphogenesis into the digital realm and applies these to an architectural case concerning real-time adaptive reuse of space. HyperCell as a cellular architectural component can operate as an autonomous entity with its own sensing and actuating mechanism, though each autonomous adaptation will have an associative impact on the overall morphology of the built form. The research thus aims at deriving the most essential information structure for optimal computing (almost like the hox gene) in a regulated sequence which will in turn be auto propagated but autonomously regulated by each cell throughout the bio-inspired systemic spatial formation. The research does not state that HyperCell is the ultimate answer for the future of adaptive re-use in architecture, but instead proposes an innovative, bio-inspired design methodology for real-time adaptive architectural and interior spaces.

REFERENCES

Camazine, S., Deneuborg, J., Franks, NR., Sneyd,J., Theraulaz, G. and Bonabeau, E., 2003, *Self-Organization in Biology System*, Princeton University Press, New Jersey.

Carroll, S. B., 2005, *Endless Form, Most Beautiful*, W.W. Norton & Company, Inc., New York.

Frazer, John, 1995, *An Evolutionary Architecture*, AA Publication, London.