TOWARD A BEHAVIORAL DESIGN SYSTEM: AN AGENT-BASED APPROACH FOR POLYGONAL SURFACES STRUCTURES

ABSTRACT
The following research investigates the development of an agent-based design method as an integrative design tool for polygonal surface structures. The aim of this research is to develop a computational tool that self-organizes the emergence of polygonal surface structures from interaction between its geometric constituents. The research focuses on the ethological level of morphogenesis that is relevant to the animal or insect societies, whereby agents mediate the material organizations with environmental aspects. Meanwhile, this study investigates behavior-based approaches as a bottom-up system to develop a computational framework in which the lower-level elements constantly interact. The geometrical definition of grid structures is abstracted into building blocks or agents to construct the agent’s morphology. The abstracted principles that define the agent’s morphology are then aggregated into a generative tool to explore the emergent complexities. This exploration coupled with the generative constraint mechanisms steers the collective agents system toward the cloud of solutions; hence, the collective behaviors of agents constitute the polygonal surface structures. This polygonal system is a bottom up approach of developing the complex surface that emerges through topological and topographical interaction between cells and their surrounding environment. Ultimately, the agent-based parametric model, with embedded morphological features and significant behaviors, establishes the integrative methodology, which replaces a knowledge-based design system.
INTRODUCTION

In recent years, integrated design processes have been investigated to coordinate between various sectors of building construction. Most integrated design processes are knowledge-based systems developed around a common database that links the design intention to the final designed outcome. This top-down system establishes a linear organization that is restricted to early design stages and considers an integrated design tool where the design, as the ultimate form, imposes its definition to the construction systems, while the construction systems, in turn, limits designers to comply with their constraints. Although the process of rationalization is mediated between defined forms and fabrication tools, the concept of computational morphogenesis (Menges 2008) investigates the development of inseparable integration processes between form generations and materialization processes.

In general, integrative design processes emphasize natural morphogenesis in which the pattern formation is contiguous to the process of materialization. Therefore, the computational morphogenesis is used to study natural formation through different approaches of morphology, e.g. functional, constructional, and theoretical. These approaches formulate computational morphogenesis by considering the constraints of constructional morphology such as morphogenetic (or fabricational), phylogenetic, functional (Seilacher 1970), and environmental factors (Seilacher 1991). However, theoretical morphology is comprised of morphogenetic simulation and morphospace construction, requisites for generating organic form (McGhee 1999). Therefore, the synthesis of those two aspects of morphology (constructional morphology and theoretical morphology) proposes an integrative design method that considers material organizations, fabrication tools, and contextual environments as active design drivers. The computational model that encompasses these active drivers requires a bottom-up system in which the self-organization of lower-level elements generates adaptive behaviors to explore emergent and unpredictable complexities.

One promising method to integrate these separated drivers into one computational model is an agent-based system. An agent-based system as a bottom-up approach generates behavioral characteristics that arise during the process of interaction between agents and their contextual environment. In addition, agent-based systems consider communications between multilayer behavioral systems, embedded within the agents and environmental stimuli to trigger the corresponding behaviors. These systems, which are applicable for computational morphogenesis, consider form as a state of dynamic equilibrium that derives from the correlation between material features, micro/macro environmental factors, and fabrication procedures. The emergent form through this interconnected correlation directs the design towards the high-level of integration that cultivate an effective performance in contradiction to the integrated design optimization and process of rationalization.
The presented paper focuses on an agent-based design computation tool to generate a novel structure with a polygonal surface assembly that investigates the abstraction process of polygonal systems, while considering the aggregation criteria, to accumulate these assemblies into one structural system. Based on this integrative method, the tool then examines two levels of system organization, to control the complexity of integration, and to coordinate the aggregated system to exploit the form emergence. In this method, the self-organization and emergence utilize a bottom-up approach to assemble individual polygons that aggregate into a single, complex surface. The emergent complexity at both the micro and macro levels are investigated to organize this adaptive system which regulates the overall state of the system whereby simultaneously the agent’s behaviors modulate the environment and the environment modulates the agent’s behaviors.

**AGENT-BASED MODEL OF MORPHOGENESIS**

According to Turing’s theory, morphogenesis designates the development of form and pattern in an embryo in which morphogens react and diffuse to generate a spatial pattern in correlation with a chemical concentration gradient (Murray 1990, p. 119). In the embryological pattern formations, the mechanism of form differentiation and articulation relies on chemical and physical properties, geometrical and mathematical processes. Within the context of animal and insect societies, the morphogenesis process can comprise ethological pattern formations related to the individual and collective agents’ behaviors. Therefore, the behavioral morphogenesis has two categories, one where the agents are part of the behavioral pattern (e.g., flocking, and ants building bridges), and another one where agents are involved in the process of form generation, i.e., agents build their own nests or colonies (Bonabeau 1997, pp. 193-194). The contribution of agents in morphogenesis provides the basis for developing a behavioral system in which agents mediate as active parts between the processes of formation and materialization.

Ethological insights of agent mediation provide the notion of behavioral organizations in which agents’ behavior emerge from their reaction to both environmental stimuli and adjacent agents. Hence, the agent has its own specific morphology that interacts with environments based on the embedded rules. Similar to the constrained generating procedures or CGPs (Holland 2000, p. 126), these rules contain the both generative procedures and constraint mechanisms. The restriction processes embedded in the agents inhibit the agents’ behavior in which the generated behaviors adapt the internal properties to the external factors. These behavioral adaptations converge agents system to a cloud of solutions, effective to their ecological niche.

In addition to the behavior-based approach, agents modulate the ecological context and, in response to environmental stimuli, adapt their behaviors to new situations of the modulated state. The bilateral modulation entails an internal coordination system to synchronize agents’ action with their embedded primary goals. The behavioral system,
a bottom-up process, facilitates the agent to amend its behavior to the various contexts effectively. Therefore, the behavioral system can be defined in two levels: internal and external. The internal level emphasizes stabilization of the agent’s morphological structure and the external level retains adaptive synergy with related environments. Similar to animal behaviors, the internal behavior of agents presents a homeostatic system whereby external influences change the agents' configuration.

In homeostatic approaches, internal mechanisms check for deviations and based on the results, transmit signals to the control systems to adjust these deviations in order to return the system to the stable state (Manning and Dawkins 1998, p. 31). The deviation tolerances are defined based on comparisons between the current state and the stable state of an agent's morphology that regulates the internal consistency of that agent's structure. The process of self-regulation derives from feedback control in which these mechanisms, as a part of the control system, evoke the homeostatic agents. Thus, the homeostatic agent continuously adjusts its behavior to remain within the deviation tolerance. The external mechanisms also related to the internal system by which the control system is developed as coordination mechanisms. In a behavior-based system, the coordination system correlates between different behaviors and based on different mechanisms trigger appropriate responses. However, in both of these behavioral controlling systems (i.e., correlated to the internal and external behaviors), the evaluation mechanism is established through checking the arising states within the system, and by positive and negative feedback, it regulates the agent's behaviors.

BEHAVIOR-BASED MODEL OF MORPHOGENESIS

The behavior-based system is employed for integrative design computation, whereby the collective behavior as an emergent complexity represents dynamic adaptations within the complex system (Baharlou and Menges 2013). This bottom-up structure is associated with integrated competences (Maes 1993, p. 3) to generate a cloud of proper solutions for such behavioral systems (Miller and Page 2007, pp. 78-79). The cloud of solutions insists on a variety of appropriate responses instead of achieving one optimal solution (Holland 2010, p. 17). Although the variety of responses is related to the development of integrated competences in agents, the competences can improve the cloud of responses through generative integrations of design and fabrication factors. Hence, the cloud of solutions is effective by considering the morphospace of fabrication tools where the fabrication constraints are considered within the process of morphogenetic design.

In agent-based modelling techniques, the autonomous decision-making units can be developed into a behavioral integrative system where associated material properties and fabrication constraints are abstracted into each unit. The generic abstraction of material properties, geometrical characteristics, and fabrication tools requires that the integration of abstracted entities exhibit emergent phenomena. Based on the level of
abstractions, these entities can be embedded within computational models in two ways; agent-based objects, which focus on the modelling of the lower level structures, or abstraction-based objects, which insist on modelling the system as a whole (Miller and Page 2007, pp. 65–67). In terms of behavior-based systems, agents are associated with generative processes of bottom-up approaches to exploit or explore lower-level behaviors, for example, exploring the local interaction between individual elements at micro levels to negotiate the ultimate capacities of the systems at macro levels.

The exploration of lower-level behaviors considers aggregation techniques. In complex adaptive systems, aggregation techniques are applied to simplify the complex system in which the system entities, which have only slight differences in proliferated details, are aggregated into one category as building blocks (Holland 1995, p. 11). This institution considers a redefinition of the complex system by expanding the organization of abstracted entities. This implies a hierarchy of behavior-based systems, which are attained through interaction between abstracted entities, whereby it considers having the same type of morphology with specific performance. Consequently, the aggregation technique establishes a method which organizes bottom-up features of complex adaptive system to exhibit the characteristics of emergence (Figure 1).

In integrative design computation, the agent-based systems emphasize emergence and self-organization due to the dynamic complexity of interaction between active drivers (e.g., material, fabrication and environmental drivers). The emergent properties of these behavioral organizations lie on two levels: micro and macro. The micro-level interactions between lower-level elements generate macro-level emergent behaviors, required by the system to be able to fulfill an effective self-organization to overcome resulted complexity (De Wolf and Holvoet 2005). In addition, the behavioral system simplifies abstracted criteria in the agent’s data structure to reduce inessential computation during the process of integration. Consequently, the active drivers are abstracted into specified classification by which the related behaviors emerge through their interactions within the system. However, the controlling mechanisms evaluate the behavioral responses and coordinate them to select proper actions.

Figure 1
Agent’s adaptation is related to different topological systems that are exhibited through Network neighborhood, Von Neumann neighborhood, and Moore neighborhood.
SURFACE STRUCTURES AND GRID SHELLS

An early example of gridshell structure, the “Multihalle” Mannheim—Frei Otto and Carlfried Mutschler, 1975—represents the negotiation between material characteristics, structural properties, and fabrication processes. This unique shell system with the complex geometry of double curvature establishes a self-organization insight for grid structures in accordance with the material properties. In addition, this self-organization presents the scalability property of form-finding procedures due to the emergent complexity of the free form attained through material behavior organizations. The interrelation between geometric systems (cells or lattices) ensures that the depletion of one lattice is inconsequential to the overall system performance. The collective behavior of lattices together establishes the stable free form surface that arises from interaction between lower-level elements.

The self-organizing system has been investigated in different projects to integrate surface structures with design intentions (Tamke et al. 2010; Parascho et al. 2013) in which the structural system is abstracted into an agent-based design computation to generate a self-organized grid structure. The process of embedding lattice structures into agent-based systems is an effective design approach due to the behavioral integration that occurs among different design factors. Although the interactions between each one of the lattices are in accordance with topological or topographical rules, it is necessary for any self-organized system to be adaptive rather than of predictive. For example, fixed topological rules establish self-organization properties that facilitate the manipulation of system components. These fixed topological procedures conform the system to the predefined stable states; they are incapable of adapting the system to the arising conditions and further user interactions.

As a result, the adaptive system is essential to self-organize the polygonal systems where flexible topological and topographical rules constitute the polygons. Therefore, this polygonal system requires effective rules to assemble for the lattices in order to achieve a polygonal surface structure. In addition, the polygonal accumulation describes a geometrical method to develop agent’s morphology in which it follows the behavioral system to facilitate the lattices assembly. The method conducts evaluation mechanisms to control the process of differentiation and integration. This controlling system consists of evaluation mechanisms for checking behavioral responses and coordinating them. Ultimately, the behavioral approach to agent-based design computation provides a method to assemble lattices for exploring polygonal surface structures.

COMPUTATIONAL SETUP

Rationalization of a free form surface is realized through geometric algorithms that discretize the complex surface into the fabricatable components. In that regards, the triangulation and quad mesh algorithms are applied in architectural design to generate
shell structures or polygonal surfaces, for example, the Expo Dach in Hanover (Herzog and Partners 2000), the Great Court at the British Museum in London (Foster and Partners 2000), and Centre Pompidou in Metz (Shigeru Ban and Jean de Gastine 2010). Contrastingly, the “Multihalle” gridshell as a complex surface offers another method in which the structural behavior of material systems is involved in the process of form generation. This behavioral form generation is an effective modelling process to establish a computational framework in which the grid cells interact with each other based on the topological and geometric procedures. These procedures organize controlling mechanisms to inhibit their interactions and their computational framework, which facilitates these setups, and consist of agent-based systems, where material system and behavioral assembly mechanisms entrench within the agents.

In ethological morphogenesis, agents are the active part of pattern and morphology formation into which they entail geometrical morphologies and related behaviors. Therefore, the computational setup, which models complex surface formation, requires the abstraction of polygonal systems into simple geometric systems. The geometrical structure of lattices describes the active morphological system for an agent in which the agent’s behavior corresponds to the embedded morphology; hence, there is a cohesive relation between the agent’s morphology and their behaviors. The abstraction of these polygonal systems attains the bottom-up features that describe agent’s geometrical structures and behavioral responses to the external influences.

In agent-based design computation, agents interact with each other constantly and their interactions follow the geometrical features that are abstracted from their morphology. In addition, their morphology imposes specific rules for assembly as various lattices interlock together to generate a free form structure. The geometrical structure of complex surface refers to a collection of discrete convex or concave n-gons (multi-sided polygons) which are tied to the surface curvatures (e.g. synclastic or anticlastic surfaces). These n-gons are the categorization sets of nodes and internodes in which they constitute agent systems of simple morphological descriptions, i.e. points and lines (Figure 2). Therefore, the two parts are significant, the first one is the vertices and understanding the number of links connected, and the second is the number of agents, which are sharing the same links or edges.

Through the hierarchical organization, the computational model establishes procedures to obtain the categorization mechanisms that aggregate nodes and internodes to define agents. The number of nodes and internodes attains different polygonal geometries, in which they realize the agent’s morphology as a higher level of aggregation. The aggregation delivers accumulation of agents around one common nodes that designate a valence. The valence controls the number of agents to assemble in one-shared nodes. Hence, the aggregation of various agents in the shared valence generate a meta-agent in which similar meta-agents follow related rules and based on that they have an explicit response to the comparable external stimuli. This categorization continues
to meta-meta-agent as another level of aggregations. Based on definition of interaction mechanisms between meta-agents, different categories of meta-meta-agents will emerge in which system-integrated competences define the numbers of polygons and their relation with environment through different generating procedures and constraining mechanisms (Figure 3).

The number of connections with other adjacent nodes controls the behavior of valences, for example, each node can be associated with more than four adjacent agents that results in different types of polygon (e.g., pentagon, hexagon, and heptagon). In aggregation level, such structural diversity generates unpredictable emergent complexities (Figure 4a). As an adaptive process, the variation of valences with different connectivity numbers develops a heterogeneous articulation of several meta-agents in one organized system, as a meta-meta-agent (Figure 4b). This adaptive behavior utilizes a computational tool for design by changing agent’s factors that differentiates complex surfaces with diverse types of topology.

This computational tool models a cohesive structure in which the interactions between its components demonstrate self-organization and emergence, and these properties are conceived through control mechanisms that modulate the internal and external interaction between constituents and coordinate system towards the emergence assembly. The control mechanism dictates the deviation tolerances of the agent homeostasis in the micro level, where the consistency of agents requires retaining the morphological definition of agents, giving way to a morphological consistency that includes the geometrical planarity and equilaterally of fabrication constraints. For example, the planarity of agents’ morphology is maintained through constant evaluation of their node coordinates, and based on this evaluation, the average deviation of nodes’ coordinates are steered agents toward the accurate tolerances. In addition, the control system at the micro-level preserves the agents’ consistency to generate emergence in the higher, macro level (Figure 5).

The control system regulates the design computation tool based on the topological connectivity within edges and valences. These properties act as active elements embedded
in the agents, which collectively stimulate the complex surface as an emergent form. Engineering self-organization and emergence processes attempts to stabilize the complex dynamic systems and avoid any disturbance during the process of simulation and modelling. This consistency of the elements responds to the environment that, as an active agency, ensures that the agent-system behaviors converge towards the cloud of behaviors. The environment can then be defined at two fields of active and passive. The active field is defined as a field of forces in which the forces change the agents behaviors and the passive fields as the target surfaces that agents lay on that and adapt to different surface curvatures (Figure 6).

**DISCUSSION AND CONCLUSION**

Development of the behavior-based approach has priorities over the knowledge-based approach, as this approach is the expression of lower-level features and specifies the opportunity to embed basic material characteristics as well as fabrication constraints. Definition of simulation models in the role of building blocks provides low-level interactions within the modelling environment to exhibit emergent complexities. Computational models for exploring such interactions are associated significantly with the abstraction methods of material properties, fabrication constraints, and environmental factors within the primary generative mechanisms. Accordingly, agent-based modelling with low-level of knowledge facilitates the generative integration between form generation and materialization processes. Generative integration means behaving within the problem domain instead of knowing it; this system is utilized through theoretical and constructional morphology to improve behavioral responses where material properties are coupled with fabrication constraints. Therefore, the behavioral morphogenesis emerges from agents’ data structures that are established through morphogenetic simulations and morphospace constructions. These embedded features allow agents to investigate appropriate solutions in relation to the adjacent agents and the contextual environment.
In addition, the abstraction techniques comprehend the effective methods for embedding abstracted components into the agent-based system. One issue in the abstraction embedding is achieving a state of equilibrium due to the dynamics of the system. Hence, this issue arises from constant interaction within the generating system that produces new states for agents in each iteration. In this case, all agents must simultaneously reach the equilibrium state, since any failure in reaching this state by each one of them will cause an imbalance for the entire system. In case of failure, all agents would start developing new explorations on the problem domain. Although a given agent state may occur inside the cloud of solution, this solution state may not meet the designer’s intent. Therefore, the generative agent-based approach requires the augmentation of adaptability by self-organizing procedures to explore emergent properties within the solution space. Thus, agents can improve their behaviors through intervention of the user during design exploration (Figure 7). In other words, the integrative design in contrast to the knowledge-based system requires adaptive processes to enhance the level of its ontology gradually, since all agents will converge to the developed behavioral solutions while they have access to the rest of the other agents’ data-structures.

Figure 7
Agent adaptability to the user interaction: i.e., users can fix individual agents (A/B) in space and the surface agents form accordingly.
REFERENCES


EHSAN BAHARLOU

Ehsan Baharloo is a doctoral candidate at the Institute for Computational Design (ICD) at University of Stuttgart. He holds a Master of Science in Architecture with distinction from the Islamic Azad University of Tehran. Along with perusing his doctoral research, he has taught seminars at the ICD since 2010.

ACHIM MENGES

Achim Menges, born 1975, is a registered architect and professor at the University of Stuttgart, where he is the founding director of the Institute for Computational Design since 2008. He also is Visiting Professor in Architecture at Harvard University’s Graduate School of Design since 2009.