New Methodologies in Architectural Design inspired by Self-Organization

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This paper introduces a potential application of construction systems seen in biological systems to overcome various shortcomings in human architecture. Unlike human constructions, some social insects can produce habitable structures with simple rules without predetermined blueprints or central leaders to gain more adaptability. Active application of logics from self-organizing systems can possibly enhance our conventional centralized methods by designing artificial distributed systems. A conceptual case study is presented that involves a notion of the collective construction.
1 Introduction

In architecture, global configurations or formal geometrical gestures are often defined by a principal architect—as a single intelligence—from the outset of the design process, and the rest of the requirements for buildings to properly function are post-rationalized by many people under the leader in hierarchical (top-down) manner while maintaining the initial configuration established by the leader. This top-down construction process historically worked quite well in architecture, and has successfully produced many masterpieces. Building designs led by several different principal architects occasionally fail to achieve clear conceptions in their visual forms and their integrities, and often end up as patchworks.

However, recent demands for planning and design of buildings with multiple occupants and inhabitants numbering several thousands are becoming a challenge, and may exceed one architect’s design capabilities to solve the potential complexities. Furthermore, recent advancements in engineering allow architects to envision building structures on mega scales, and to introduce additional layers of complexities into the building design. While the design of small to mid size buildings may be within one architect’s design capabilities, the design and planning of large projects with several thousand inhabitants is a challenge. Meanwhile, many creative formal results by leading architects are gaining a new level of plasticity due to the recent technological advances in material sciences and structural innovations; however, those new emergent forms are not always the results of performatively optimal solutions with respect to environments, occupancies, circulation, and so on. Creating aesthetically inspirational geometries which can truly reflect the buildings’ performance is a challenge for many contemporary practitioners. New methods are being sought to address these emerging complexities.

2 Self-organization in Collective Construction

In contrast to the construction processes by humans, the Collective Constructions seen in nature, accomplished by wasps or termites, indicate the existence of fundamentally different construction principles based on completely different logics and behaviors. Firstly, wasp or termites do not have awareness of the global goal of their constructions. Unlike human constructions, no predetermined blueprints are available throughout the constructions, and it is doubtful that there is ever any awareness of the final configuration or convergence in their mind during the construction. Their process does not depend on supervisors or central leaders monitoring their progress and giving instructions. (Figure 1) The critical difference from the conventional centralized human design method is that the self-organized internal logic inside the system is able to search and design without knowing its transcendent global target in a bottom-up manner, rather than casting and limiting the final form or gesture in a top-down manner before fulfilling all the requirements.

This self-organizing system, often seen in social insect behaviors, is a decentralized problem-solving system that consists of relatively simple interacting entities. In a decentralized system, each individual gathers information on its own and decides for itself what to do based on its local properties, and this activity is carried out in dynamic fashion. Unlike the convergence toward the static preconceived goals in some human activities, continual dynamic interactions among simpler lower-level entities produce and maintain the goals. In these systems, the goal itself is an ever-changing property and requires continual interactions. These characteristics make their problem-solving approaches very ‘flexible’ and ‘robust’. Flexibility in self-organized systems means being adaptable to constantly changing environments. Robustness is their ability to function as a whole regardless of some imperfection in performances at the local lower level of components, which means that failures to perform tasks by some individuals in the system are not always fatal to the entire system’s ability to function. Even though individual entities do not possess sophisticated cognitive capabilities, aggregation of these entities interacting in dynamic fashion based on simple locally distributed rules is able to maintain and direct the system toward the globally optimal solutions. Of course, human systems also possess this type of tolerance for unpredictable conditions to some degree. However, it is likely that the tendency to seek perfection and immediate efficiency is more significant in human systems than in...
**Figure 2.** Sets of local rules to grow structures.

**Figure 3.** Evolved configurations based on the fitness.

**Figure 4.** Examples of structures evolved autonomously in evolutionary run. Configurations are based on the fitness evaluation.
biological systems, and there may well be some valuable knowledge to be gained from investigating and adapting those systems’ behaviors.

One well-known example of a self-organized, distributed system is the beaver’s ability to build lodges and dams from branches, mud, and other debris. According to Camazine, et al. (Camazine, et al 2002), beavers do not seem to rely on any innate concept or blueprint of the structures they build. Instead, the authors speculate that their building behaviors are genetically programmed responsive acts which are triggered by beavers’ surroundings. This kind of stimulus-response is often called Stigmagy (Grasse, 1959) by researchers. Stigmagy is an important notion for understanding the process of collective constructions. In this notion, information from the local environment under dynamic progressions stimulates and guides further activities in construction. A certain local state of the system becomes an incentive for the next construction for individual workers, and this process continues to feed new information for the builders. In this way, information is always provided from the dynamically changing environment rather than any source of information external to the ongoing construction activities. This is one of the reasons why social insects, such as termites, can undertake complex constructions without the knowledge of the ultimate form of the structures. This Stigmagy often refers to the information collected from works in progress. The consequential resulting products of these collective activities are often thought to possess emergent properties, and Emergence refers to “a process by which a system of interacting subunits acquires qualitatively new properties that cannot be understood as the simple addition of their individual contribution,” according to Camazine, et al (Camazine, et al 2002).

These processes are completely different from any existing conventional design processes which we have seen in human architecture so far. Our design process is relatively a top-down manner, and oftentimes blueprints or global gestures are known in advance or imposed by leaders at the beginning of their design stages. The existence of a well-informed leader is a quite common characteristic in human group activities, as a majority of our corporations in societies possess top-down hierarchical organizational structures. In contrast, design processes in wasp and termite colonies are bottom-up processes, and their final formal configurations are the results of optimization by locally distributed multiple intelligences.

Many formal and structural engineering aspects of natural and physical systems have been well investigated and successfully applied to various synthetic objects in our daily life including architecture. Natural distributions of structural forces seen in branches of trees, soap bubbles, or formations of sea-shells have been an inspiration for many architects. Structural elements in Gothic churches often mimic trees, and Gaudi in the 19th century further developed biomorphic forms to take advantage of natural force flows in organic shapes. The formal aspect of architecture has been strongly influenced by various biological structures.

However, relatively internal and logistical aspects of biological systems, such as collective behaviors seen in aforementioned collective construction, have yet to be clearly analyzed and applied to our synthetic design processes, particularly the cases where there is no blueprint or recipe for global configurations available or defined. In the area of computer science, increasing numbers of scientists are starting to pay attention to self-organizing systems, particularly those seen in the social insects, and they try to draw on these systems to devise problem-solving methods. This approach focuses on the characteristics of self-organization, such as distributedness, flexibility, robustness, and interactions among relatively simple agents. Most of the applications so far have been in the areas of combinatorial optimization, communications networks, and control algorithms for robotics (Deneubourg 1990). But even in computer science, not all of the applications are anywhere close to practicality yet, though the researchers are definitely well aware of the potential advantages of the bio-inspired distributed systems to remedy many weaknesses in our existing centralized control systems. Eventually, their goal is to design artificial distributed systems that self-organize to solve problems and replace conventional centralized control by using inspirations from social insect behavior.
3 Methodology

Theraulaz and Bonabeau are two of the pioneers who provided the computational interpretations for the logics behind the collective constructions by wasps (Theraulaz 1995). The following conceptual experimentation is inspired by their works and intended to provide architectural interpretations in the speculative domains of methodologies for constructions.

In this purely conceptual experimentation, the ultimate objective is to gain cohesive structure solely from locally assigned series of construction rules without providing any global information about the structure (such as blueprints). The experiment takes place in the hypothetical lattice space inside a digital environment, and numbers of construction agents are distributed inside the lattice space. Series of rules (instructions) indicating the proper placements of construction blocks, based on the $3 \times 3 \times 3$ neighborhood conditions, are originally randomly generated and given to the agents, and they place the building blocks as they find the stimulating configurations which match the given rules. With this method, they can continue to construct the structure based solely on the feedbacks from local dynamic neighborhood conditions in concurrent fashion. By iterating this process for a certain period of time, agents will produce structures corresponding to the given rules. Based on the rules and the combinations, their resulting structures can be either deterministic or non-deterministic and occasionally have some probabilistic variations in their growths, since the movements of agents are not defined deterministically. Potentially, design tendencies or the likeliness of certain patterns are describable with a few rules instead of requiring complete resulting forms. Use of a relatively abstract form of design descriptions, "Rules", is suggested in this method.

The next step for the experiment is to auto-generate and select the fittest set of rules by providing the evaluation criteria for arbitrarily produced populations of building structures. Construction using every set of rules is performed until the structures cease to grow or the numbers of iterations exceed a certain threshold. Populations of sets of rules are compared and evaluated according to the resulting structures. Then, based on evaluation, rule-sets that score higher fitness values will be considered as elite sets and remain as parent sets for the next generation's schemes. For every rule in every set, the numbers of times that they are stimulated are recorded, and the rules that are used more often are ranked higher among the rule-sets. (Figure 2) The rules that are never stimulated during the simulation will be discarded from the rule-set (extinction). New generations of rule sets are produced by simple cross-over between aforementioned parent sets, and a mutation process adds a randomly generated new matrix of rules to prevent the search from stagnating within local search spaces. The above iterative process is based on the genetic algorithm (GA) developed by John Holland (Holland 1992). For the sake of clarity, the fitness criterion that was chosen for the experiment was based on simple local checkability. The aim is to direct the evolution toward the formation of larger clustering patterns. For every block in the resulting structures, the numbers of identical matches of local neighborhood cellular configurations are checked, and the matches in the neighborhoods with the larger radii (up to 5 units) are considered to have higher fitness, as it implies similarities on a larger cluster scale.

The results indicate the appearance of some coherent structures in earlier generation (Figure 3&4). We recognized self-similarities in some structures which resemble the Sierpinski triangle. Once the numbers of blocks exceed certain numbers, growth seems to converge on simple filling of the lattice or alternating grids. Dividing the above fitness results by the number of cells generated is one strategy to penalize excessive growth, and to avoid high-density solutions. Using hard-coded rules that guarantee the generation of coherent structures as the GA's initial population, instead of randomly generated rules, is another strategy. However, initial rules are gradually replaced by cross-over and mutation after a few generations and eliminate the initial population's influence on geometries. Due to the purely computational nature of the experiment, selection of proper fitness criteria has become a profoundly complex issue beyond its architectural interpretations. What appears to be coherent in numerical format does not always give us visually recognizable patterns. This discrepancy between our intuitive visual perception and our numerical implementa-
This fitness criterion can, theoretically, be designed carefully to implement complex conditions to assimilate real-life scenarios in architecture. Further, I extended the notion of generative grammar based on simple construction rules to the control of an industrial robot to auto-generate desired configurations based on constraints of the gripper arm and the stackability of blocks as hypothetical construction units for my recent experimentations (Figure 5&6).
4 Discussion and Critique

In architecture, few structures have ever been built or conceived based on the active application of the aforementioned logics from natural systems. Excluding some of the emergent formations of cities on larger scales over longer spans of time, adaptation of self-organization to architectural creations is an uncultivated area of study worthy of investigation. Although there are some studies of urban-scale phenomena using agent-based models, I believe that we have yet to fully understand the latent potential of self-organization, distributed systems, and collective intelligence in the context of architectural applications. It is not simply an investigation of novelty in style, trend, mode, or superficial formal representation. It is a search for an evolution—fundamentally, a new attitude toward the creation of artifacts among us.

Ironically enough, the fact that we humans can occasionally build highly sophisticated, yet dysfunctional objects, can be considered proof of our being superior to the other species in some respects, or at least an indication of unique characteristics inherent in human intelligence. Motivations toward collective goals beyond merely functional or practical outcomes are rarely seen in any other biological species besides humans, but it is quite easy to find such examples in the field of architecture when we consider the current formally articulated trends in the discipline. They are an indication of our aptitudes for more advanced intellectual activities and productions. These behaviors or creative tendencies are perhaps one such natural consequence of humans being capable of storing more information; thus immense information for globally more complex configurations can be handled by individual members as a blueprint.

Nevertheless, our construction processes—even at practical levels of applications—do not seem to have reached the stage of perfection yet; they may well be on the brink of a necessary transition from conventional centralized schemes to more distributed systems. Having complete knowledge about the final global objectives in construction is getting increasingly difficult as the scale and complexity of the buildings start to exceed our capacities for individual comprehension. Indeed, humans have limited processing speeds and cache spaces as individuals. Considering that the termites’ and wasps’ nest constructions require more than the period of their individual lifespans, and some of their nest sizes (in relation to body size) are way beyond the scale of any human structures ever built, we have yet to rival the magnitude of their construction scales and durations. One species of termites called *Macrotermes bellicosus* are known to be able to build structures over 30m in diameter and 6m in height (Grasse 1984), and the size of the structures in proportion to human height is over a mile (Howse 1970). These facts may indicate the existence of methodologies that can possibly enhance our conventional understandings of habitats.

5 Conclusions

The experiment described in this paper suggests that structures directed toward certain properties can be describable purely by locally implemented processes—“rules”—instead of providing a complete set of blueprints, so that the structures can in principle continue to grow with the dynamic changes from the external environment or circumstances associated with the structure.

One remarkable finding from the observations of collective construction by insects is that their processes do not seem to have a discrete design phase before the construction. Design, construction, and operation are seamless concurrent activities in their processes, and these characteristics help them to gain significant flexibility in their habitat designs. Development of flexible and adaptable architecture has been a perennial theme among practitioners, and some of the failures among the Metabolists in the 60s (Frampton 1992) clearly indicate the difficulties of designing universal subunits that could endlessly tolerate technological, environmental, and circumstantial changes associated with structures. In order for structures to self-assemble and dynamically grow, the scale of the movable or replaceable components needs to be examined, as our structures at architectural scales are under different magnitudes of influence from physical forces such as gravity, compared to wasp nests or cells in slime mold. Simple adaptation of distributed logics in morphologi-
cical aspects of design alone will not be adequate to realize truly adaptable intelligent structures. Consistent adaptation of distributed concepts throughout all phases of projects may be an essential principle for the evolution of robust and flexible structures. Processes of coming future structures may not possess discrete phases such as design, construction, operation, reuse, and demolition; the alternative task for us may be encoding the spontaneous growth of structures as a genotype, rather than providing complete sets of static blueprints.

6 References


