Similarities and differences between humans' and social insects' building processes and building behaviors

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ABSTRACT

Despite of the simplicity of their individuals, social insect societies are structured social organizations that accomplish complex tasks which far exceed the individual capacities of a single insect. These self-organized systems offer possibilities for inspiring new and future solutions and technologies to benefit human construction practice. Biomimetic research of this kind studies systems that have evolved in the natural world in order to imitate and apply them in processes to benefit humans. We present the social insects' main building-behavior principles and their potential to influence the building industry and human building processes, considering process stages and durations, communication and information flow, governance, functional specialization of workers, supply chains and materials. We review existing biomimetic applications in different fields related to construction management with respect to biological swarm systems and social insects in particular. Finally, we identify opportunities for examining and enhancing building construction processes, inspired by the behavioral principles of the social insects.

Keywords

Agent-based simulation; Biomimetics; Construction engineering and management; Coordination; Social insects' building behavior.

INTRODUCTION

Although biomimicry research is common in architecture and materials engineering (e.g. Gruber 2011, Rebolj et al. 2012, Stachelberger et al. 2011), it is a relatively unexplored in construction engineering and management (CEM). The few existing biomimetic applications are mostly based on swarm intelligence and social insects. They have been limited to the use of mathematical algorithms to solve optimization problems (Afshar et al. 2009, Ng et al. 2008, Lam et al. 2007, Dimitrijević et al. 2012), development of intelligent automated systems (Petersen et al. 2011, Parker et al. 2006, Stewart 2006), and in a few cases to direct implementation of biological behavioral principles (Christensen 2013).

Social insects (ants, termites, bees, and wasps) construct complex nest structures while employing decentralized control, autonomy and distributed functioning, self-organization, and stigmergy. Stigmergy is a form of indirect communication through the environment (Holland et al. 1999, Dorigo et al. 2000). Social insect colonies show that very simple organisms can form swarm-systems capable of performing highly complex tasks by dynamically interacting with each other.

In contrast to traditional models and algorithms for construction that are based on centralized command and control, there is a growing interest in expressing and enhancing processes using distributed control algorithms. Researchers started studying the behavior of social insects and their adaptive capabilities in an attempt to study and develop collective construction (Peterson et al. 2011). The research efforts on collective construction were done mainly within the disciplines of intelligent autonomous systems and robotics. Some of these concepts may suggest further inspiring insights from the point of view of civil engineering in general, and construction management in particular.

Until today, animal behavior and computer sciences researchers studied the building behavior among social insects, yet without the point of view of how this kind of information regarding the biological building processes can be applied to human building practices. The motivation for comparing the two behaviors is in the new perspectives it may yield. Comparison between social insects' and humans' building behavior may interestingly result in pragmatic conclusions which could be helpful to any project manager. The existing knowledge base and observations on social insects is spreading, and in the era of interdisciplinary thinking, it is now possible to make this analogy and to wonder what can we learn, what have we already learnt, and how biological processes can further inspire innovation in construction processes.

COMPARISON OF SOCIAL INSECTS' BUILDING BEHAVIOR AND HUMAN BUILDING PRACTICE

In this chapter, we present a 'first-pass' comparison between human construction practice and social insects' building behaviors, comparing a variety of CEM aspects. The comparison is summarized in Table 1.

Process Stages and Durations

The development of a human construction project may be divided into distinct consecutive stages (such as design, tendering, fabrication, construction, commissioning, and operation and maintenance). With social insects, on the other hand, the stages of the building process are sequenced differently due to the absence of a blueprint of the nest. Social insects do not hold a "predetermined" design of their construction, but rather they act through local cues and templates, such as pheromones or the physical state of their nest-mates and the constructed building, and in other words – heterogeneities in the environment (Théraulaz et al. 2003). In this way, each of the building process stages is shortened, and the design, fabrication and construction, are done generatively and essentially simultaneously.

A good example of such a process, composed of short simultaneous stages, is that of wall construction by ants, as observed by Franks et al. (1992, 1997). In the first stage of the construction work, builders individually transport sand granules (i.e. building blocks) into the nest, towards the cluster of their nest-mates, who are already located in the center of the nest. After coming close to the cluster, the builder then turns through 180 degrees to face outwards and drops the building block at a distance that sets the required nest size according to the size of the ant colony. The builder actively pushes the granule it is carrying into other granules already in the nest (or in other words – bulldozing the building block). In so doing, the builder estimates the density and stability of the existing wall under construction; this can be considered to fulfill the function of a structural analysis or testing of the situated building state.

Table 1. Summary of Comparative Characteristics of Social Insects' Building Behavior and Human Construction Practice

Parameter/ Characteristic	Human Construction Projects	Social Insects' Nest Building Projects
Process Stages and Durations	Design, planning, construction.	Site selection, emergent construction.
Communication and information flow	2D and 3D drawings, models, documents, direct verbal and non-verbal communication, feed through, articulation work.	Stigmergy (an indirect form of communication), stimuli "cues", response threshold towards stimulus.
Workers' organization and governance	Centralized control, distinct hierarchal levels, working teams.	Distributed control, self-organization.
Workers specialization	Different defined professional roles	Multi-skilling
Supply chains and materials	MTS, MTO, ETO components; dependence and waiting waste of materials.	MTS only re-use of materials; no material waste.
Competition and Waste	Waste of waiting for materials, equipment, information, preceding task completion.	Re-use of materials; dismantling of previous work in some instances; unnecessary movement of materials.

Significantly, the builder performs the design and assembly stages simultaneously. Consequently, the ants maintain minimal waste of materials, and they provide themselves with a nest cavity that is neither too large nor too small (Franks et al. 1992). Building may continue long after the initial construction phase. The rearrangement of granules in the wall may proceed for days or even indefinitely after the ants have moved into their new home, as they operate and maintain their nest.

Human construction methods and processes, on the contrary, are far more complex and technically sophisticated, and they also exhibit greater process variability than the ants' nest construction process. However, the lean construction principle of pull flow (Howell 1999), which determines production rates according to established downstream demand rather than meeting pre-planned forecasts, appears to mimic the swarm process.

Communication and Information Flow

Social insects are not able to communicate directly with each other; rather, they approach construction tasks by following intensifying cues and local interactions. The term 'stigmergy', originally introduced by Grassé (1959), explains the coordination and regulation of construction activities in social insects. Stigmergy basically means 'inciting to work'. The incitement is considered to come from existing products of labor, not directly from other nest-mates' instructions. The beauty of such mechanisms is that the ants do not communicate their building intentions to one another directly but communicate indirectly via the building structure itself and through the evidences of work previously accomplished in the constructed areas. In this way, work is added to existing work following intensifying cues (Franks et al. 1992, Karasai et al. 2002).

Nest construction by ants provides a good example of intensifying cues. Observations showed that the first materials brought into the nest site are apparently assembled to extend one of the already existing supports of the nest. In this way the ants use an existing structure as a focal point for further building. Likewise, also a large group of granules might act as a focal point for more construction work. Further intensifying cues in the form of environmental change in the construction site can be seen when ants construct the peripheral wall of their nest, which functions also as the construction site "border"; In the first stage of building the peripheral wall almost all ants deposit building blocks from the inside of the construction area. The ants build the wall from the outside only much later, when easy passage into the nest is blocked (Franks et al. 1992).

Therefore, the most rapidly constructed elements act as the strongest stimuli for further building. These elements tend to continue to grow more quickly, until the stimulus for further building declines. Stigmergy provides the initial positive feedback. The declining perceived-need for further building is defined by the term 'Response Thresholds'. Response thresholds provide the negative feedback in the latter stages of the process, as the limit which must be exceeded by increasing amounts of stimulus in order to make an insect switch tasks (Franks et al. 1992, Franks et al. 1997, Delgado et al. 2000, Petersen 2008). When an ant works on one task, say 'bulldozing' building blocks (sand grains) close to the wall, the threshold towards that stimuli will be lowered, whereas the threshold towards all other stimuli will be increased. When an environmental change occurs, such as absence of building material, another stimulus may increase enough to make the ant switch tasks into building material foraging.

As opposed to social insects which communicate through stigmergy, communication and information flow in human construction projects are done through different information exchange tools, such as 2D and 3D drawings, models and documents, verbal and non-verbal communication, articulation work, and feed-through. The initial stages of design deliverable outputs are used to coordinate and to transfer information between different roles in the project. Therefore, except for feedthrough and articulation work, most of the information transfer methods are dependent on and produced during the design stages.

Feedthrough is a cooperative communication method which can be compared to the concept of stigmergy (Dix 1997, Christensen 2012). It corresponds with the meaning of stigmergy because it explains how an individual worker acts in relation to the physical evidence of work previously accomplished. In the context of CEM, feedthrough may be defined as the sharing of information when a construction worker is aware of and responds to the effects of another worker's actions in the construction site. It may also deal with the sharing of information when a designer (e.g., architect, structural engineer, etc.) operates in response to the changes and constraints revealed during a supervision visit. Articulation work refers to the ways in which tasks are discussed, divided, and coordinated in advance of their performance. Construction work may be articulated by Gantt charts and weekly meetings, among other methods.

These last two forms of communication and coordination in construction work are often more important than verbal, non-verbal, or graphic communication. They are effective because, as like stigmergy, they are closely tied to the work itself. Articulation work give rise to distributing the tasks on an integrated concrete level. Feedthrough is implicit, unconsciously noticed and acted upon (Dix 1997). Both exhibit effectiveness and emergence in control similar to stigmergy, which in some cases seems to operate as a signal system according to which insects react and distribute tasks in real-time, without their choice or any insight of a master plan.

Workers' Organization and Governance

Social insects' motivations are derived from hormones and stigmergic signals, while human behavior motivation is derived from materialistic and moral incentives. Insects' structures emerge on a global level from the actions performed by the individual workers as they self-organize; as opposed to traditional thinking which treats human construction as guided through centralized control.

Self-organization is a process where some form of global order or coordination emerges out of the local interactions between the components of an initially disordered system (Heylighen 2001). A number of studies of social insects have shown how self-organization is involved in their collective pattern formation.

Unlike insects' governance, human building processes are usually modeled, in classical approaches, as centralized control governance mechanisms. Until the 1990's (approximately), most researchers and practitioners held the view point that there is effective "central control" behind every construction project even at the production level, where detailed construction plan and schedule were created in advance based on well-defined resource and temporal constraints (Morris 1994, Hendrickson et al. 1998). Once a plan was created it was assumed that the project would (or should) evolve according to the plan and that interaction of construction crews and individuals would have a minimal impact on this evolution.

However, recent thinking suggests that production in construction may be better understood as emergent, dependent on the individual motivations and behaviors of individual crews and workers, as seemed in insects' world through local interactions (Sawhney et al. 2003, Watkins et al. 2009). Agent-based Modeling (ABM) is typically used to study and describe dynamic behavior in social insects. This approach was found to be better also for simulating construction works, since ABM describes the behavioral characteristics of each agent by sensing changes in a dynamic environment. Moreover, there is evidence that on-site construction activities often exhibit decentralized behavior best described using bottom-up models, such as the insects' models, because they give rise to the reflection of interactions between individual components on the construction site.

Professional Specialization

Social insects are multi-skilled. Each individual performs a range of different tasks, according to the current stimulus, as they self-regulate the distribution of workers on different tasks (Beshers et al. 2001). However, an individual insect is more likely to perform the same action he performed before, if it encounters the same stimulus, decreasing the response threshold toward stimulus even more. Slowly, the insect can become specialized in a particular task until a new stimulus (e.g., hunger) gives sufficient rise to switch tasks (e.g., food foraging). In smaller colonies workers need to switch tasks constantly, whereas in larger colonies more specialized workers may be found (Petersen 2008). On the other hand, in human practice crews and individuals have different defined professional roles.

Supply Chains and Materials

Observations have shown that in most cases Leptothorax Longispinosus ants provide themselves with only a single entrance to the nest construction area. At first, the building materials are fairly scattered at the construction area of the new nest. However, it was observed that the ants gradually concentrate building materials into one particularly large pile. It was also observed that in majority of cases, the location of this pile was opposite to the entrance of the construction area. Moreover, the largest concentration of building materials is located by the ants in the direction from which they had emigrated or in closest direction from which building materials were most readily available (Franks et al. 1992).

One feature of the 'bulldozing' behavior is that ants drop their granule only if they meet sufficient resistance. If they are unable to push their building block into the wall they may carry it to another site or leave it so that it remains separated from the rest of the wall. Such relatively isolated granules are likely to get in the way of other ants and be removed and hence, eventually, taken to reinforce other, weaker, walls. Ants commonly transfer building blocks from one wall to another repeatedly. Although this results in material redistribution, the supply may be erratic and involve extensive unnecessary transport of materials.

Observations show that when ant colonies have choice between large and small sand grains, they usually show initial preference for big grains but afterwards they chose grains of both sizes (Aleksiev et al. 2007). Such preferences can be explained in terms of the structural benefits of constructing walls as a mixture of two grain sizes, while the initial preferred big grains could use for the consolidation and foundation of the nest's wall. Therefore, the structural situation of the constructed wall itself may provide cues for the prioritized material in order to construct an approximately optimal mixed wall.

While human construction supply chain practice is composed of components stock or order driven, insects are using only stock driven supply delivery. Make-to-stock (MTS), make-to-order (MTO) and engineered-to-order (ETO) are methods in supply chain management, describing different supplies according to the different roles and destinations of the delivered material (O'Brien et al. 2010). Whereas insects seem to use solely MTS component of supply chain, with building materials which may be placed anywhere, in a modular approach, according to the required structural and environmental performance requirements. Insects may use any grain size, and partial foraging preferences can have many benefits: different choices by different foragers and even individual 'error' tendencies might benefit with the collective intentions in forms of re-use, and lack of waste.

Competition and Waste

Observation on ants have shown that building can occur in several sites at once, even though there seems to be a tendency initially for the biggest existing walls to grow most quickly, as mentioned before. It was shown that the oldest part of the wall, which is usually placed in opposite to the entrance, becomes progressively thicker. The materials are placed in the center of the wall, giving a stimulus for wall reinforcement all around the nest, except in the entrance itself. This process involves strong positive feedback; so strong, in fact, that in a number of observed cases, two adjacent sides of a nest can be completed fully before any work is done at all on the other two sides. In this situation ant-workers are picking up materials not just from outside the construction area but also from other piles inside the nest site. In other words, different ants and neighboring walls appear to compete with one another for materials (Franks et al. 1992). The described competition for materials might exhibit also some disadvantaged redundancies, and as mentioned before, building blocks may be transferred from one wall to another repeatedly.

DISCUSSION AND CONCLUSIONS

The management and production control of building projects are complex subjects. A wide range of the parameters involved are dynamic and highly variable. Analogies to social insect behavior offer the opportunity to investigate both advantages and disadvantages of autonomy, distributed functioning and self-organizing building behavior, as opposed to traditional engineering methods relying on control and centralization.

Future studies that comprehensively compare natural processes to construction building processes may allow identification of possible adaptations. While mathematical algorithms inspired by social insects' sorting behavior offer easy and translatable usage among engineering researchers, taking behavioral concepts into account is less common in the scientific technological field, and requires a trans-disciplinary, or humanistic, approach which is in more accordance with behavioral paradigms. Correspondingly, it can be seen that the most relevant example by Christensen (2013) is made within the field of cognitive systems.

Classic work in insect-inspired construction (e.g., Théraulaz et al. 2003, Linardou 2008, Ladely et al. 2005) considers the forward problem of what kinds of arbitrary structures will be generated using a given rule set. We suggest on focusing on the inverse problem, starting with a predetermined structure, defined using BIM, and finding social insects' inspired rule sets to carry out the construction works on the construction site through simulations. Several studies have considered other issues related to swarm construction, such as programmed self-assembly or multi-robot systems assembling a structure composed of communicating-blocks (Petersen et al. 2011, Théraulaz et al 2003, Holland al 1999). However, these studies treat the structural environment as a cellular grid, and therefore they don’t consider predetermined large-scale realistic and habitable structures.

Many of the described research in swarm intelligent and collective construction were done by researches within the disciplines of intelligent autonomous systems and robotics (Petersen et al. 2011, Ladely et al. 2005, Adamatzky et al. 2000, Holland et al. 1999, Peterson 2008, Stewart et al. 2006), animals behavior and psychology (Bonabeau et al. 1999, Théraulaz et al. 2003) and in few cases architecture (Linardou 2008) . In years to come, one could expect more integrated approaches between computer sciences and civil engineering where swarm intelligence based models will be used for solving real-time production control problems. The challenging research problems for the swarm intelligence algorithms applications could be in simulations of production control and construction management with applied realistic predetermined structures.

Social insects' building behavior principles hold a promise in application to construction management and building processes, because this approach is not just a specific computational tool, but also a concept and a pattern of thinking. Currently there are no theoretical results to support some of the explained concepts. Good experimental results may help and motivate researchers to try to derive theories in future research. In years to come, research in the area of swarm intelligence applications in CEM could help us find the answers to the following questions: What is the real potential of social insects' building concepts in management of building projects? What are their limitations? Can an ABM simulation using complex realistic predetermined structures represent a construction process performed by insect-like agents, and how will its results differ from ABM simulations with human-like agents? How does the information sharing mechanism influence final system performance in terms of Work In Progress (WIP) and Cycle Time (CT)?

Future research should study both advantages and disadvantages of autonomy, distributed functioning and self-organizing capacities in relation to traditional engineering methods relying on control and centralization. Optional future research may include developing an agent-based simulation model for studying and improving production control in construction processes, with a view to demonstrating the utility of an emergent, self-organized mode of production control on a construction site by comparing it directly with a traditional top-down command and control mode.

First, a simulation should be developed, modeling human behavior in a construction project. This simulation should be robust and validated by attempting to calibrate it with field observations. Unlike the few existing research models, the simulation should be situated in a realistic environment modeled using Building Information Model (BIM).

Second, new insights should be drawn using the developed and calibrated simulation. The purpose would be to study opportunities for improving work flow by applying self-organization giving rise to decentralized, distributed, self-healing systems. Agents' interactions will exhibit the interdependence of individual workers and crews as they interact with each other and share resources, following the concept of stigmergy. The envisaged emergent mode functions through interactions between individual workers and crews as they flow through the project and communicate with each other and with a BIM that describes the product. The effects can be measured using Work In Progress (WIP), Cycle Time (CT), and efficiency of the operations.

Furthermore, it may also be useful to consider how concurrent workflows of design, fabrication, and assembly, in close relationship with sensing demand, could lead to smoother workflows. There is much similarity between the insects' process principles and different approaches of combined and concurrent engineering in construction. It is broadly recognized today that a close relationship between design and construction are important in the planning of facilities, and that construction projects can best be performed as integrated projects (Evbuomwan et al. 1998, Love et al. 1998). Whereas construction is the implementation of a design envisioned by architects and engineers, numerous operational tasks must be performed with a variety of precedence and other relationships among the different tasks, which require the presence, attention, and intervention of the designers (Hendrickson et al. 1998).

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