Swarm Intelligence in Architectural Design

Sebastian Wiesenhuetter(✉), Andreas Wilde,
and Joerg Rainer Noennig

Laboratory of Knowledge Architecture, Faculty of Architecture,
TU Dresden, Dresden, Germany
{sebastian.wiesenhuetter,andreas.wilde}@tu-dresden.de,
joerg.noennig@mailbox.tu-dresden.de

Abstract. This paper investigates the application of swarm intelligence in the field of architecture. We seek to distinguish different fields of application by regarding swarm intelligence as a potential tool to support the design process, to improve architectural use and further create novel building systems, based on self-organization principles. In architectural applications, swarm intelligence offers a high potential of resilience, and solutions that are fit to the task. We analyze two case studies, one concerning adaptive buildings with intelligent behavior, and one in the field of algorithmic design which makes use of agents during the planning process. Regarding their potentials and deficits, we propose a broader perspective on agent based architectural design. By integrating self-organized construction processes that are related both to the design process and to the usage, we propose combining the different tendencies to a more resilient system that covers a buildings ontogeny from beginning to end.

Keywords: Multi-agent design · Adaptive building · Evolutionary design · Distributed construction · Programmable matter · Architectural ontogeny

1 Introduction

This paper investigates the application of swarm intelligence in the field of architectural design. The scope of investigation includes both the design processes, as well as the resulting behavior of buildings in their physical environment. We seek to distinguish different fields of application by regarding swarm intelligence as a potential tool to support the design process and to improve architectural use and further create novel building systems. The benefits of this approach rely mainly on the principle of Self Organization. Self-Organization is given in cases of local interactions that lead to emergent order in an overall form or resulting structure. This is not only found in Swarm Intelligence but also in Evolutionary Algorithms [1]. Architectural design processes are enormously complex as it is a constant challenge to unite different simultaneously demanding tasks in one building without intriguing another. It has been found that these approaches can lead to emergent qualities in design. Thus both methods have been used in the field of architecture before [2, 3].

Whereas swarm intelligence achieved a remarkable relevance in mathematical and technological fields, it is still widely untapped in architectural contexts especially in professional practice. In architectural applications, swarm intelligence offers a high

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potential of resilience, time- and material- efficiency and solutions that are fit to the task. The problem of lacking "task fitness" and the subsequent deficit in architectural methodology has been addressed by Alexander [4] and others [5].

In recent years, mainly since 1970s two main strategies have been established in order to address such problems by help of distributed intelligence. On the one hand a new approach can be seen in terms of adaptive buildings with intelligent behavior, that are often directly inspired by natural processes [6]. They seek to provide better fit to changing tasks or environmental conditions through a range of possible solutions. On the other hand the field of algorithmic design has been established [7], which makes use of Swarm Intelligence strategies during the design and planning process.

The natural self-assembly processes which can be seen in bees and ants results in extreme adaptability, complexity and regularity within their construction [8].

2 Scientific Background

Architectural thinking is a highly creative process that goes beyond finding solutions to specific problems. The deficit of current design approaches is their limitation on mental capabilities and personal convictions of the individual designer who bases his decisions on tacit knowledge and personal experiences. Thus, the traditional approach, usually understood as creative process cannot compete with the possibilities of parametric design, especially if it comes to reaching a larger variety of options [6]. The author of a design program has the task to conceptualize rules, and in case, behavior of agents. Criteria of fitness, set by the author himself, can replace or support the designer's decision for a certain solution. The common attribute of any computer aided design is that both human designer and computer need to interact and communicate in order to reach a design solution. Therefore, the externalization of design methodology is crucial. Verbalization allows translation, automatization and a further leading progression of solutions. Today within the professional practice of architecture, these parametric design techniques are only implemented to a small extent. Those applications, however, rarely exceed the boundaries of parametric modeling, and even then, often stay object centered [5] and static design approaches. The design process of architecture usually does not make use of codified methodology, as it can be found in most fields of science.

Parametric design can be understood as a general verbalization of design processes, which enhances progress in complex design [10]. Parametric modeling itself does not use the full potential of parametric design. Additionally verbalizing requirements or methods instead, is necessary to gain new and fit-to-task solutions. Still, architecture is a field that can, until today not be fully abstracted into parametric values, and even simple abstractions already lead to an enormous complexity that is not yet in full control.

Historically, relations between society and architecture were often stable and only evolving simultaneously over many generations. Single buildings were usually not endangered to lose functional relevance over the years. Sustainable architecture was possible and ordinary within those boundaries, as buildings adapted to their function. This also led to relatively long life cycles or efficient renewal features that are often missing in contemporary architecture. Our environment today is more dynamic than it used to be. Innovations, social changes happen within shorter time spans, and buildings are usually planned for one certain recent use, no matter what following generations might make of it. The two potential reactions on a more dynamic environment could either be to plan with shorter buildings ontogenies, which is a strategy that is currently in use. Buildings today are usually planned for only 30 years, and indeed, buildings often change their function after only a few decades. The other option would be to follow strategies of adaptive architecture that is not static but dynamic itself, changing with the demands of society, climate, political system or simply a new user. This strategy is technically demanding, but allows a better sustainability concerning energy-resource- and time efficiency [4]. Christopher Alexander proved that architectural design can be seen as multi objective optimization, but it must be noted that the requirements that a building is supposed to acquire are constantly changing [4]. Therefore we have to see the context of architecture as a dynamic one. In its consequence, we assume the problems of architectural design as dynamic multi-objective problems (DMOP) [9].

We assume that there are comprehensive principles of Swarm Intelligence that can support the whole process of architecture. Recent progresses in computational design support research on adaptive features of architecture. The aim of this adaptive architecture is to precisely match to buildings requirements. The key in this new approach is parametric design. Parametric design enables application of iterative processes like Evolutionary Algorithms [1] or Swarm Intelligence algorithms that are often the key way of comparing and finding solutions. The use of Swarm intelligence - enabled by parametric design - extends the boundaries of human cognition, which then allows the finding of design solutions that are close to the designer's original intentions but are not directly accessible.

Today, we can see Swarm Intelligent approaches in two main tendencies in architectural design:

(A) Adaptive structures are real-time responsive and dynamic by reacting to environmental influences in a physical environment. This usually takes place after a construction that defines the boundaries of parameters or states that the building can adopt.
(B) In the design process, Swarm Intelligent applications can be used to optimize a defined solution to a design problem. A building can for example be optimized concerning light, structural design, layout and so forth, or according to multiple criteria. One application that could lead to emergent qualities could be Evolutionary Algorithms.

3 Approach

It is possible to design a building that makes use of Swarm Intelligence both for the design process itself and in ways of adaptive architecture during use. Those two phases of a building are usually separated by a materialization process, namely the construction (Fig. 1): The building is initiated as a space for specific purposes. After the design process the plan is converted into an embodiment. The building is then used until function and building do not correlate to a reasonable extent anymore. Restoration/renovation can prolong this time span by multiple decades. Adapting an expression from biology referring to the development of single organisms, we define a building's process from initial design to its use, adaption (for example renovations), and final demolition as ontogeny.

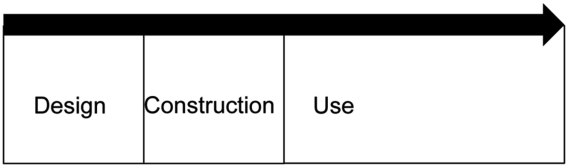

Fig. 1. 3 phases of a buildings ontogeny in their known order

3.1 Case Studies

We would like to discuss two case studies of Swarm Intelligence in architectural design as they represent the two main approaches. The first is an application during the use of buildings and is represented by a responsive folding structure. The second is the application during design phase and is exemplified by an emergent design approach.

3.1.1 Responsive Building Structure

Case Study I: Modular Multi-agent Folding Robot

This study combines two biologically inspired principles:

(a) The principle of folding which enables animals and plants to change surface properties and allows flexible movement in general. Such deployability often results in higher energy-efficiency e.g. the blooming of buds and leafs allows the process of photosynthesis from the very beginning of unfolding.
(b) The second principle is the way of controlling complex movements through swarm behavior based on local interactions.

The intention is to obtain a responsive building structure e.g. a roof which can adapt to the environmental conditions. Hence it can achieve better performance e.g. in terms of building climatic properties such as maximizing solar gains in cold surrounding while providing optimum shading without blinding. A possible scenario could include optimizing the airflow around and within a building in accordance with the current locally measured wind circulation in order to provide cooling or fresh air in hot surroundings. This example poses a complex problem since turbulences in airflow respond dramatically to even slight changes in the conditions and hence are mostly hard to predict and cope with through predefined or non-responsive configurations. The proposed strategy can adaptively "learn" and respond to unforeseen constellations. The setup uses irregular folding structures in order to achieve a higher range of possible shapes. Thus instead of precalculated configurations new solutions can emerge from the behavior. The potential of deployable folding structures for engineering and architectural purposes has been investigated and highlighted by Tachi [13]. A crucial point in rigid-foldable structures is to ensure finite motion. In our case the transition between the folding states of the global structure is constrained by the foldability at each node of the mesh structure and the current fold angles around the neighboring nodes at the same time. Hence the motion planning is rather complex and the search space for behavioral strategies is huge. Since the actual target states of movement are also subject to optimization and not predetermined it seems natural to include the task of motion planning along with this process. Thus it becomes rather a process of motion search and finding. This case study intends to deal with the complexity of these tasks by regarding each fold angle as an agent in a multi-agent-system which is physically embodied within a swarm robotic building [as seen in Fig. 2], [14]. The experimental setup consists of 22 agents, equipped with sensors and actuators respectively. The setup was developed as a testbed for different PSO algorithms.

However this approach is limited by the design of the folding pattern which has been embodied into the structure beforehand. Hence this robotic building can only behave within the range of possible states. To overcome this limitation it would require to redesign and possibly extend its folding pattern and to perform physical construction processes.

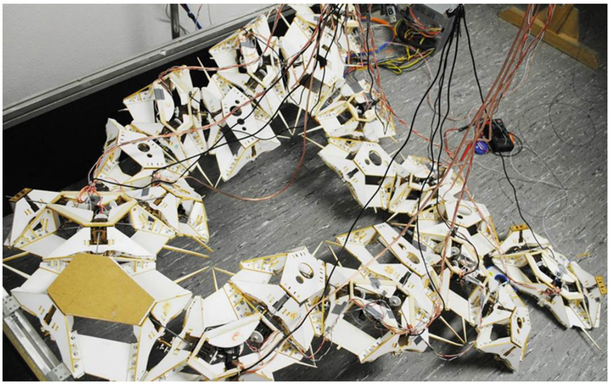

Fig. 2. Shape robot: multi-agent folding for adaptive behavior, B. Felbrich (2014)

3.1.2 Emergent Design Approach

Case Study II: Evolutionary Cellular Design Engine

The study investigates the potential application of agent based modules to Architectural Design. The objective is to utilize the emergent qualities of self-organized systems for the search of design solutions. Therefore, we formulate an experimental setup for design approaches in architecture that are generated in an evolutionary process [Fig. 3]. The setup is a virtual simulation only that is set up in Grasshopper, which is a Plugin for the CAD Software Rhino.

Research on the analogies between natural principles has led to the introduction of principles of self-organization in the architectural field. Especially swarm building behavior of termites, just as informal settlements offer a conversion from biological processes to design approaches in architecture. As a study, a generator is set up that is based on a cellular automaton. Common or uncommon rules of design are hereby integrated into the agent simulation that finally defines the configuration of modules. The specific application works with the task of layout design in case of apartment housing. This task still represents a major part of classic architectural design work. Systems Theory just like architectural theories like structuralism [15] support the understanding of buildings as systems of interrelated elements and their organization. Those modules are defined as simple room configurations like ‘Garden’, ‘2 rooms’, ‘Living Room’ and so on. Rules describe pleasant or unpleasant configurations of rooms, open spaces, directions, and the number of appearances in one house that then affect the overall fitness of the design solution. Especially interesting is the appearance of the Von-Neumann-neighborhood, both in modular space design and three-dimensional cellular automata. This similarity is used in the program. Different rooms with different states are set in relation to their neighboring modules. Those relations are finally evaluated. The applied evolutionary solver then either selects the most potent option or proposes different solutions that can be found on the pareto front.

The generator finds very performant solutions to single problems, however it’s performance concerning multi-objective problems often lacks quality. To select possible design options from a pareto front with up to 20 dimensions, the different requirements often are rebalanced in their resulting effect on an overall fitness. However, the generator does find designs that are not intrinsically found, and asymmetric, very unlike from classic housing designs.

As far as the simulation goes, we can find very suitable solutions for a virtual setup which is defined by the author. However, this simulation is configured based again on tacit knowledge and beliefs of the author that might not work accordingly in reality.

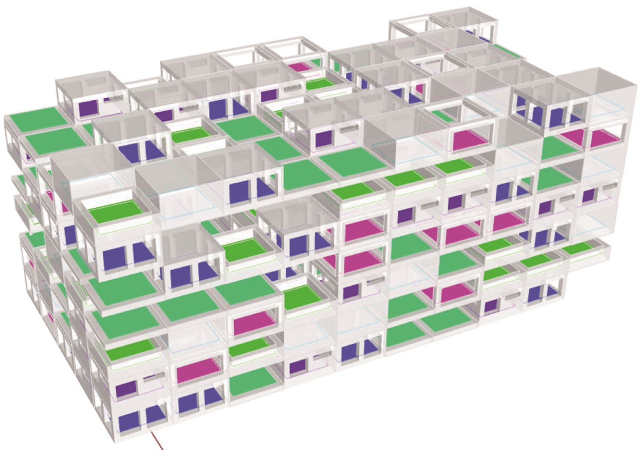

Fig. 3. Simulation engine for evolutionary optimized cellular housing design

Therefore, a Swarm Intelligent process, including the physical setup and real application could gain further knowledge and therefore update the virtual model and respond to newly emerging needs during application. Different visions of metabolist architecture sketched such settings of potentially adaptive modular housing. It is therefore an ambitious approach, but not unrealistic in the future of architecture.

4 Synthesis

As we can see Swarm Intelligence can influence architecture heavily, but those examples are very specific and do not change the principle structure of architectural ontogeny.

Swarm Intelligent applications however could change the way that buildings evolve in the construction process itself. Those processes could be self-responsive, taking place in a physical environment, being optimized in ways of efficiency in work distribution and a very short term reaction process between possible changes in the requirements of the building and the physical structure. One potential field is distributed construction by robots, like distributed 3D printing [11].

The limitation of optimizing in different phases of the ontogeny could be overcome by Swarm Intelligent processes going beyond the three different phases of a building. They could interconnect those phases and change the static order of Design, Construction and Use. Here we propose a comprehensive setup for future building systems, that interlinks strongly throughout the three phases of development [Fig. 4]. Natural processes as growth, adaptation and evolution can serve as useful analogies.

In nature, the design of an individual is firstly shaped by evolution and secondly by morphologic adaptations, namely growth processes that are based on the individual's situation and thirdly on movements, such as tropisms and nastic or rapid movements in plants. Growth and function are linked in homogenous processes. Obviously a tree is growing with nutrition it gets from its daily working functions (use), adapting to its

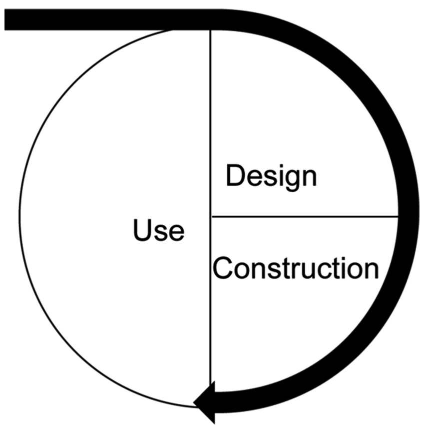

Fig. 4. 3 phases of a buildings ontogeny linked in an iterative system

very situation and place (design), growing taller and fit to its tasks (materialization). Biological design processes hence demonstrate the overlap of those 3 fields as the most potent option.

We propose an iterative time scale: The intentional design is not a final design but rather a proposition that is further evolved during construction and use. Therefore the process needs constant cycles through the states of the buildings ontogeny.

5 Conclusion

In theory, an approach of combining swarm intelligence in design, construction and use in one process could even lead to a paradigm shift in the relation of a building and time. Looking at this relation in different scales we can see 3 periods in which adaptation can take place, and in some cases Swarm Intelligence is already a part or architectural reality:

(a) Within a period of use, or situation, usually minutes to hours. One example of this would be the change of weather or the absence or presence of people in specific places.
(b) Within a buildings ontogeny, usually between one and hundreds of years. An example would be the changed requirements towards a building because of new clients or a different number of client members.
(c) Within ages of change, meaning changes that can take place in hundreds of years, like the evolution from an agricultural to the industrial age.

A major difference between (a) and (b) towards (c) is that the adaptation over hundreds of years does usually not take place within one building but can be understood in generations of buildings. Churches, for example, are in many ways still very alike to the first churches of roman times. However it is fairly easy to see significant differences between different centuries. Historically, case (c) is a case in which we can find swarm behavior shaping design, without the conscious intention to do so. Every human being can be seen as a potential agent that observes, processes and releases design.

Another scale on which different types of swarm adaptation can be found is the scale of architecture. Swarm intelligence can or could affect:

(a) the chemical configuration of a buildings material
(b) the material properties including smart properties, texture, e.g.
(c) technical components
(d) rooms or buildings
(e) networks of buildings like cities
(f) global or universal scale

Swarm Intelligent structures that already exist are especially found in the big scale of villages, cities and so on, and eventually in a very small scale, concerning chemical configurations that are rarely studied. This is due to the size and complexity of a single agent. Human agents can be found in the cases (e) and (f) but not in smaller structures.

What we can see in cities as a case model of agent based design is that the stages of the cities ontogeny are not happening after another but simultaneously, very alike to the morphology of organisms. This feature, the ontogeny without separate phases, could possibly be adapted to an architectural ideal model. This results in structures that evolve in an integral process including design, construction and use.

Hence, we propose an extension of this current state of Swarm Intelligence in Architectural Design. By integrating self-organized construction processes that are closely related to the design process and to the usage, we combine the different tendencies to a more resilient system that covers a buildings ontogeny from beginning to end [Fig. 5].

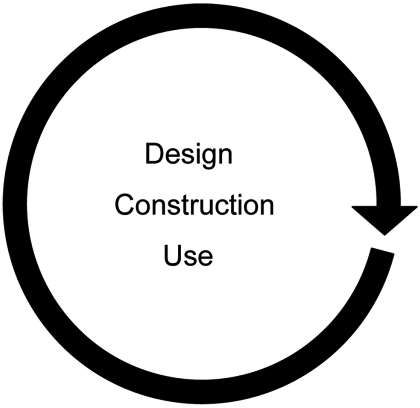

Fig. 5. 3 phases of a buildings ontogeny taking place simultaneously

However we have to note considerable differences between biological organisms and a house in terms of adaptation that lead to the conclusion that natural design is not an essentially suitable model for physical architectural adaptation. It is a very own feature of evolution to fail in single instances while leading to emergent solutions in the scale of species and ecosystems. Architecture needs to avoid failure at any cost. Failing could either mean a lack of fitness of a given solution, or fitness criteria that do not correlate to actual needs or interests. It has to be noted that those interests or needs, are, even in a fully agent-based emergent design theory, still defined by human beings. The proposed model cannot exclude the verbalization of a design target, and doesn't answer the question of how to verbalize architectural needs.

If we refer to a virtual simulation of physical spaces, individual solutions that lack quality are welcome, and even necessary for optimization. We have to note that virtual simulation is inevitable in architectural adaptation if we want to make use of evolutionary optimization. In those cases, optimization must take place prior to the process of materialization. In an overall swarm intelligent system however, this optimization must not lead to a definite design intention but could refer to the process of construction or would rather describe the structure instead of the explicit space it defines.

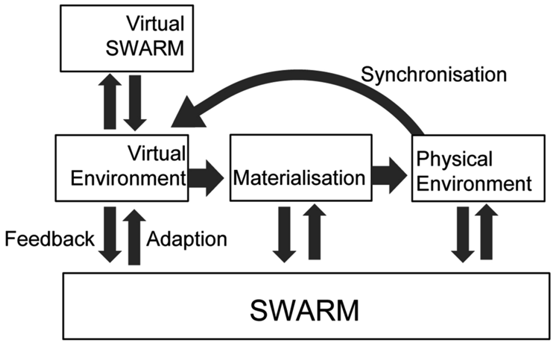

Fig. 6. Swarm processes affecting all aspects of architectural design

In a concluding proposition of Swarm Intelligence in architecture, we see a feedback- and adaption-relation between the physical swarm and the three states of the buildings ontogeny [Fig. 6]. The virtual environment is a simulation environment for a virtual swarm representation. This swarm is potentially making use of evolutionary algorithms to constantly simulate and select different up-to-date options that are then materialized to become part of the architecture in its environment physically. The virtual environment is finally synchronized with any active or passive change of the physical environment to find correlating adaptations. The swarm is therefore part of the virtual environment and part of the physical design but also the agent materializing design. This results in agents that have the following features: (a) ability to sense environment, (b) self-monitoring (c) gather and sending information to a virtual swarm application (d) adaptivity of the agent's state (e) growth by changing the number of agents or amount of material (f) reconfiguration.

However we have to note that applications including virtual swarms and physical swarms in a synchronized set up, could potentially lead to higher resilience, without the features (e) and (f).

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