Chapter 1
Visions of Process—Swarm Intelligence and Swarm Robotics in Architectural Design and Construction

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Abstract This chapter discusses and reviews the application of swarm intelligence (SI) and swarm robotics (SR) to architecture and construction from a history of science and technology perspective. In a first step, it explores the conceptual entanglements of swarm intelligence and adaptive environments and situates them in the context of a recent theoretical discourse about "media ecologies". The second part provides a critical overview of seminal SI approaches for architectural design. These scrutinize novel connections between architecture as a site of material composition and as a site of spatial practices by computer experiments in software environments. Its guiding hypothesis is that SI technologies here are primarily used to create *diversity*. Subsequently, the third part of the chapter examines in which ways recent advances in collective robotics lead to further materializations of the adaptive capabilities of swarming that go beyond software applications. It presents three state-of-the-art examples of SR for architectural construction and demonstrates that SR in architectural construction—in contrast to the paradigm of *diversity* discussed in the context of architectural design—work best in context with a high degree of standardization and pre-defined modularization, or, on the basis of *regularity*.

1.1 Introduction

Swarm Intelligence (SI) has inspired—and sometimes haunted—architectural thought and architectural design for more than two decades. In 1994 Kevin Kelly, at that time editor of Wired Magazine, enthusiastically embraced Mark Weiser's (1991) vision of ubiquitous computing devices:

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[A]s chips, motors, and sensors collapse into the invisible realms, their flex-ibility lingers as a distributed environment. The materials evaporate, leaving only their collective behavior. We interact with the collective behavior—the superorganism, the ecology—so that the room as a whole becomes an adaptive cocoon. (Kelly 1994: 150).

As of today, we realize that such 'superorganisms'—at least at the consumer end—are called Alexa or Siri, and that behind the distributed devices of such ambient and adaptive intelligences lurk the monpolistic and centralist data mining forces of tech giants: the data leeches behind the swarm. Ten years after Kelly and Weiser Kas Oosterhuis (2006) more specifically described the potentials of swarming for a renovation of traditional architectural approaches in a dawning age of digital networks and tools. Surrounded by the emerging accessibility of open source and free software his *Swarm Architecture* manifesto on the one hand became a conceptual framework that conceived of buildings as dynamic point clouds which mesh a multitude of building elements, inhabitants, and their actions (see also Friedrich 2009), whilst on the other called for novel collaborative work modes facilitated by digital technologies. It spawned a number of experimental architectural buildings which involved SI software applications, e.g. *ONL's* 'Water Pavilion', or *Laboratory for Visionary Architecture*'s 2014 pavilion for Philips Lighting (LAVA 2014), and has been extended by Studio *Kokkugia* (2010) from buildings to cityscapes—architecture theorist Neil Leach called this *swarm urbanism* (Leach 2009). However, only recently such conceptual and computational SI approaches to architecture began to leave their software environments and spawned real-life cousins (see e.g. Wiesenhuetter et al. 2016): Research projects like the termite-inspired *TERMES* at Harvard University (see Petersen 2016; Petersen et al. 2011; Werfel et al. 2006; Werfel et al. 2014) or the *Aerial Robotic Construction* group of ETH Zurich which makes use of flocking algorithms (see Augugliaro et al. 2013; Willmann et al. 2012) started engineering robot collectives for actual architectural construction.

No matter whether ideas of using SI in architecture rose from wet dreams of tech advocates or concern concrete engineering problems, they refer to a particular mindset of creating viable solutions for multi-dimensional or opaque problem spaces by benefiting from the capacities for self-organization of collectives of rather simple, but highly relational individual agents. SI is grounded in the idea that the complex adaptive behavior of a system at the global level can be effected by multiple parallel interactions of very simply constructed individuals at the local level which follow a set of only a few behavioral rules. Figure 1.1 Compelling cases are the three steering rules of avoidance (avoid collision with local flock mates), alignment (steer towards the average heading of local flock mates), and cohesion (steer towards the locally perceived center of the flock) which one finds in bird flocks or fish schools, or communication through stigmergic signs which individuals leave in the environments like in some types of social insects. Such collectives possess certain abilities that are lacking in their component parts. Whereas an individual member of a swarm commands only a limited understanding of its environment, the collective as a whole is able to adapt nearly flawlessly to the changing conditions of its surroundings. Without recourse to an overriding authority or hierarchy, such collectives organize themselves quickly, adaptively, and uniquely with the help of their distributed control

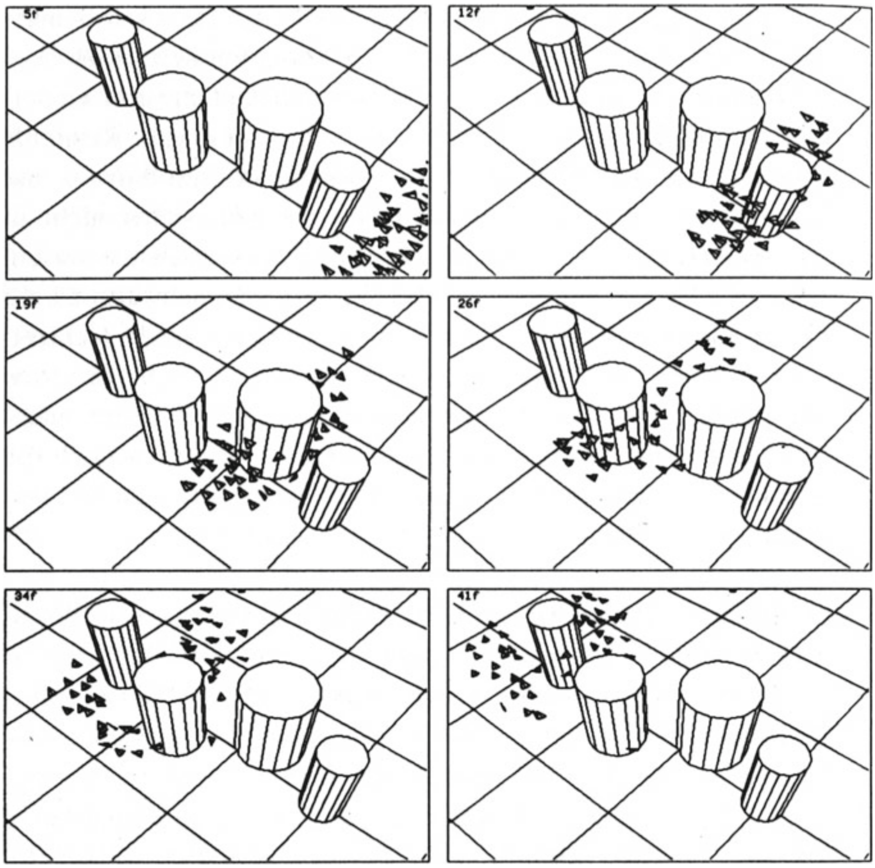

Fig. 1.1 In 1986, computer graphics designer Craig Reynolds developed a pioneering SI application known as the Boids Simulation. Its ‘bird-oid’ agents show self-organized collective movement based on a flocking algorithm of only three basic behaviors in local neighborhoods: Separation (steer to avoid crowding local flock mates), Alignment (steer towards the average heading of local flock mates), and Cohesion (steer to move toward the average position of local flock mates). The screenshots are taken from the graphic console of a Symbolics Lisp Computer. (Reynolds 1987)

logic. Within swarms, the quantity of local data transmission is converted into new collective qualities.

The epistemological foundations of that particular mindset, however, are more intricate than the usual bionic narrative of bio-inspired technical systems. Swarms, flocks and schools first emerged as operational collective structures by means of the reciprocal computerization of biology and biologization of computer science. In a recursive loop, swarming in social insects, flocking birds or schooling fish inspired agent-based modelling and simulation (ABM), which in turn provided biology researchers with enduring knowledge about their dynamic collectives. This conglomerate led to the development of advanced, software-based ‘particle systems’.

Agent-based applications are used to model solution strategies in a number of areas where opaque and complex problems present themselves. Swarm intelligence (SI) has thus become a fundamental cultural technique for governing dynamic processes (see Vehlken 2013).

Distributed, leaderless, robust, flexible and redundant, swarms adapt swiftly to changing environmental forces. Moreover, they form a specific secondary environment, which surrounds the swarm-individuals and facilitates adaptive processes by way of rapid nonlinear information transmission between these individuals in local neighbourhoods. As media theorist Eugene Thacker put it:

> The parts are not subservient to the whole—both exist simultaneously and because of each other. […] [A] swarm does not exist at a local or global level, but at a third level, where multiplicity and relation intersect. (Thacker 2004)

This third level precisely designates a specific adaptive environment, which mediates between external environmental forces and the behavior of swarm individuals.

As a consequence, this chapter seeks to contribute to a more detailed understanding of 'adaptive environments' by exploring the impact of SI—and particularly, the potential impact of swarm robotics (SR)—for architecture. It critically discusses their capability of synchronizing individual movements with influencing environmental forces. The chapter explores how their 'intelligence of movement', or 'logistical intelligence', can be exploited for constructural and building purposes. And it argues that even though the emergent and non-linear capacities of computational SI applications pose intriguing challenges to prevalent architectural paradigms like parametricism (see Schumacher 2009; suckerPUNCH 2010), and although the buzzword SI first was introduced in a paper on collective robotics (Beni and Wang 1993), the transformation into concrete building processes realized by robot collectives is by no means a next step of a linear history towards ever more refined technologies. Swarm Robotics not only pose a set of entirely different hardware and manufacturing problems, but at the same time also lead to adjustments in the conception of dynamic, self-organized design and building processes when these are confronted with the task of constructing the—mostly static—exosceletons of built environments.

The chapter is organized in three sections. The first part critically discusses the theoretical and conceptual entanglements of swarm intelligence and adaptive environments. Finally, both termes allude to a non-trivial hybridity between biological, technological and even ecological traces, terms, and trajectories. The second part provides a critical overview of a number of seminal computational approaches to architecture which derive from the SI mindset and which make use of the adaptability of self-organizing computational agents. These scrutinize novel connections between architecture as a site of material composition and as a site of spatial practices by computer experiments in software environments—be it architectural design tools that generate 'swarm effects' or agent-based models for all sorts of movements and actions of computational agents. The guiding hypothesis—which follows the lines of thought of Oosterhuis or Roland Snooks—is that SI technologies here are primarily used to create *diversity*. Subsequently, the third part of the chapter examines in which ways recent advances in collective robotics lead to further materializations of the adaptive capabilities of swarming that go beyond software applications. It presents three state-of-the-art examples of SR for architectural construction purposes and ventilates some possible benefits as well as a number of principal shortfalls: Although SR—primarily in the form of Unmanned Aerial Systems (UAS), but also as grounded collectives— since several years has developed into a thriving field with a high impact e.g. in logistics, agriculture, or the military, such collective systems seem *principally* rather poorly suited as platforms for architectural building: Besides their limitations in terms of payload capacity, they depend on a working environment which consists of easily identifiable elements, and, at best, shows a lot of regularity in the environment itself (i.e., even surfaces, etc.). If such conditions are not provided, the complexity of using SR for building purposes by far exceeds the costs and means that are needed for other (automated) building technologies. As a consequence, even if there are giant leaps to be expected in automated building and in the use of industrial robots and 3D printers (conceivably with some degree of mobility) (see e.g. Ford 2016, Brynjolfsson and McAfee 2016), the use of autonomous SR building systems *principally* only coheres to very particular environments: Not coincidentally, state-of-the-art papers from this area still resurrect robotic pioneer Rodney Brooks' idea of employing SR for space missions (see Brooks 1989) by focussing on environments where no alternative technologies are at hand, of a similar complex matter, or exhibit little aesthetic requirements. The guiding hypothesis in this third part is that—in contrast to the creation of *diversity* on the SI software level—SR in architecture work best in context with a high degree of standardization and pre-defined modularization, or, on the basis of *regularity*.

1.2 Environmentality

'Adaptive Environments' indicate an exemplary subject matter which connects recent media-theoretical discourses and approaches with architecture and design. Mark Weiser—to refer to him once again—pointed out that "the most profound technologies" of the 21st century "are those that disappear" (Weiser 1991, 94). And Matthew Fuller's seminal publication *Media Ecologies*, at the latest, raised the awareness for the fact that the development of such ubiquitous, mobile, and environmentally embedded media technologies would not only entangle sociosphere and techosphere in unprecedented ways but also emancipate both from humans as their focal point (Fuller 2005). Or, as German media theorists Florian Sprenger and Petra Löffler put it: "In the environment everything is equal—no matter if it is human, animal, plant, or thing" (Löffler and Sprenger 2016: 6). This technological development, says Fuller, can only be understood with reference to ecological modes of description which enable the combination and distinction of heterogeneous elements: These e.g. may include aspects of materiality, technology, biology, sociality, or the political (see Starr 1995). Consequently, it is not a coincidence that media theorists and philosophers like Jennifer Gabrys (2007, 2016), Nigel Thrift (2007), Luciana Parisi (2009, 2013), Mark N. B. Hansen (2014) or Erich Hörl and James Burton (2017) elaborated on these approaches and formulated extensive media-ecological concepts, and that e.g. Petra Löffler and Florian Sprenger suggested to provide some media-historical grounds to this discourse (Löffler and Sprenger 2016).

These authors update a discussion about technical environments for an era of digital cultures which unifies materiality and data transmission. Its conceptual traces, write Löffler and Sprenger, on the one hand lead back to Marshall McLuhan and Neil Postman who, in the 1960s, conceived of media history as a historical succession of media environments—from the alphabet via letterpress printing to electronic media like film, radio and television, and finally to the computer. McLuhan's and Postman's fundamental question always concerned the ways how the appearance of a new medium would transform our structures of perception, thinking, and behavior, and it shows through also in the actual discourse. On the other, it links to Michel Foucault's (2004) conception of the term 'environment' who, in the context of his theory of governmentality, described the redistribution of power relations from defined disciplinary institutions into decentralized environmental agents. But apart form this, the historical strains also point towards ideas from the fields of architecture and urbanism: Patrich Geddes and Lewis Mumford—to name but two protagonists—whisked away the term 'environment' from biology, introduced it to urban studies and cultural theory, and thus connected it with novel areas of knowledge and practice (see Sprenger and Löffler 2016: 9).

If today we speak of technizised or even adaptive environments it is mandatory to not take such terms for granted but to bear in mind the complicated conceptual and theoretical history of their becoming. Sprenger (2018) emphasizes that a profound transformation took places in the discursive trajectory of 'environment' that lead from biology to technical disciplines like architecture. In its early context, that is, in the writings of biologist Herbert Spencer who established the use of the term in the English language in the late 19th century, 'environment' indicated a virtually unchangeable, natural, self-balancing space to which every life form had to adapt to in order to survive. According to Sprenger, during the first decades of the 20th century, this point-blank opposition of environment and man-made modification lost its effective power—to pressing became the urge for controlling environmental factors: Already in the 1920s, early examples extend from ecology, e.g. forestation projects, over the construction of artificial environments as laboratories for the rapidly expanding experimental sciences, to Geddes' approaches to urban planning (see Sprenger 2018).

From there, its conceptual and theoretical history can be continued to the manifold perspectives to understand architecture as a built environment with all sorts of technological and ecological ties—a browse through the headers on arch + or AD cover pages gives a quite appropriate overview. It can be followed as a broader exploration of its environmental sustainability and a critical evaluation of its conceivable contributions to strategies of environmental engineering form a design point of view—as possible answers to the challenges of an actual all-encompassing *environmentality* (see Agrawal 2005). And eventually, it can be extended from Reymer Banham's "well-tempered environments" (1969) to media-technological innovations like digital laboratories, computer simulation environments, or even immersive computer game worlds as well as to those ambient hybrids of architecture, smart materials, and embedded information technology which today wing the steps of investors as sensor-laden smart homes (e.g. Sprenger 2015, 2014), smart cities (e.g. Halpern et al. 2013; Thrift 2014; Kitchin et al. 2017), intelligent workplaces (e.g. Hartkopf et al. 1997), or assistant systems.

The focus on feasible *adaptive* potentials of environments adds a novel twist to the conceptual genealogy of technical environments and exceeds questions of environmental modification: Instead of elements (organisms, things) which *are contained* trying to modificate the containing environments, it now is the containing environment which modifies itself with regard to the necessities of the contained elements (organisms, things). And this twist concurs with an epistemological conversion: McLuhan, in his short text *Message to the Fish* (McLuhan 2001) conveyed that the only thing that fish had no clue of was water—the immediate environment, the containing medium being totally self-evident and taken for granted. He thus alluded to the unreflected adaptation of humans to media environments which he sought to break in furtherance of a critical analysis of his present. Notwithstanding, in the context of adaptive environments this perspective is turned topsy-turvy. Here, it is necessary to explore what the environment knows about its contained elements (organisms, things), how it generates this knowledge, and how it applies this knowledge. Herbert Spencer's organisms which struggled to adapt to an equilibrial environment, as well as later attempts to technically modify, stabilize, or level environmental conditions in the favour of the contained elements are replaced by an environment which adapts to the changeability and the dynamics of its contained elements. Or, to put it another way: Adaptive environments require a theory or a concept of the contained elements to be able to adequately interact with them. And its development becomes all the more demanding the less standardized these elements are or the less predictable they behave. Or, to put it yet differently: The problem of contingency which always complicated the adaption of individuals to environmental forces also works in the opposite direction if technical environments are meant to adapt to the irrationalities and eventualities of contained elements.

In this line of thought, SI and SR can be perceived as exemplary adaptive environments because they approach complex organisation problems by means of artificial *populations* of agents and their behavior in time. The movement paths and vectors of populations, not geometric principles, account for this novel architectural approach. Based on a small number of basic behavioral rules in local neighbourhoods swarms swiftly react a reconfigure themselves dynamically with regard to external disturbances whilst providing the swarm members with a secondary environment that enhances their individual capacities. Architectural design and construction can benefit from the algo-rithmic logics of SI and SR in various ways. First, its mindset extends the possibilities of handling and optimising the complex interplay of various input variables for building processes. It integrates the levels of individual movements of particles (simulated humans, traffic flows, winds, etc.) at the mesoscale of single buildings and at the global level of urbanscapes. Second, the agent collectives—if appropriately tuned—will self-organise in a number of probably interesting or desirable forms over the iterated runs of numerous scenarios, thus transforming the understanding of planning and construction processes. From this change of perspective, architecture becomes based most notably on movements. Moreover, this generation of forms develops in ways that would not be comprehensible without the media-technological means of agent-based computer simulation. Third, it introduces a novel kind of futurology into architec-ture. With computer experiments in ABM software, a great number of different scenarios can be tested and evaluated against each other, offering insight into a variety of different desirable futures. Fourth, this rapid prototyping of possible scenarios in combination with automated procedures of scenario evaluation by evolutionary algorithms introduces a zootechnological and post-humanist element to the design process that can be extended to mass-customized production processes, resulting in a large diversity of forms and shapes in building elements. It thus coalesces more traditional (human) cultural practices of architectural design and construction with novel media technologies. Fifth, the capacity of adding ever more elements to ABM allows for a seamless synthesis of multiple ideas, or for a feedback of opinions by customers or future users during an ongoing design process. And sixth, with SR the prospect of translating such autonomy, flexibility and dynamism to architectural construction is substantiated.

The synthetic character of SI and SR is founded on an underlying algorithmic structure which defines neighbourhoods among all kinds of objects. As an effect, space—in the software and CGI environment of computational swarms and agent-based models as well as in the collective construction procedures of swarm robotics—has no longer to be organised or constituted by a defined geometric grid, but self-generates out of the multiple local interactions of point clouds, particle swarms, or communication signals between robots. SI and swarm robotics act as adaptive environments as they clarify and enable a perspective on space as a computation environment. As Kas Oosterhuis (2006, 14) puts it:

> Taken to the extreme all material is a form of information, and taken even further all information is a form of computation. Thus space computes information. The question to be raised here is: does the space compute or do the people in the space compute? In the context of Swarm Architecture I understand human action in such a way that it must be the space which does the trick. The space is full of more or less active components, many of them communication with each other, many of them interacting with certain intervals, and many of them interacting in real time. […] How can we look at space with this in mind? Then it is the space itself that behaves and acts, as driven by their programmers and executed by a variety of actors, among them people, but also light bulbs, refrigerators, vacuum cleaners, sofa's, shopping, bookshelves, tables and chairs. They all move or are moved inside a certain space. In the mind of the Swarm Architect, all actors/players behave in relation to each other following a set of simple rules. And it is the space which defines the workspace of the players.

If the main difference which is produced by architecture is the one between inside and outside—as systems theorists from Niklas Luhmann to Dirk Baecker (1990) have claimed—then SI and SR operate as mediators at this exact threshold between inside and outside, at the same time integrating external environmental forces and internal individual forces, and thus processing knowledge of either side.

1.3 Diversity

Swarm Intelligence and Swarm Robotics are entangled from the onset. In 1988, Gerardo Beni and Jing Wang were giving a short presentation on so-called cellular robots—at that time an emerging field of computational methods based on the use of cellular automata—that is, "groups of robots that could work like cells of an organism to assemble more complex parts"—at a NATO robotics conference when in the ensuing discussion they were asked for a buzz word "to describe that sort of 'swarm'." Beni and Wang (1993) took up this suggestion and published their paper with the title *Swarm Intelligence in Cellular Robotic Systems*: A term had been coined which interestingly was first picked up e.g. in fields like biology or in (mathematical) optimization, and in logistics and epidemology (see e.g. Bonabeau et al 1999, Kennedy and Eberhart 1995), transforming the 'cellular robots' and the abstract CA time- and space grids of the 1980s into more flexible ABM. Long before maturing into a technology which was embodied in actual robotic collectives, Beni's and Wang's 'robots' performed their SI in software environments—as computational agents. Nonetheless, the significant principle remained unchanged: "The production of order by disordered action" which appeared to Beni and Wang as the basic—and intriguing— characteristic of swarms (Beni 2008b: 153).

When considering how SI and ABM systems help to treat complex architectural problems, one has to distinguish between two strains of self-organization principles: The one looks at the dynamical generation of (architectural) forms in social insects, the other is occupied with the dynamic movement and adaptive capacities of flocks or schools on the move (like birds or fish). For architectural design, they serve several functions: First, they can be used to produce idea models—that is, inspiring new shapes for further design measures—as an outcome of emergent processes. Such idea models would not have taken on form without the algorithmic logic of SI and ABM (Mammen and Jacob 2008). Second, they can be used to represent the dynamics of existing architectural spaces in a simulation system, facilitating a play with parameters and a testing and evaluation of different scenarios. Third, SI and ABM models from other research fields—for instance, from evacuation studies or pedestrian and traffic simulation (see Helbing 2009 for an overview)—can produce relevant insight which could be integrated in the design processes. And fourth, novel fabrication techniques like mass-customization or 3D printing can be attached to these computational tools which translate the virtual models into material fabric.

The social insects principle relies on a communication structure that uses *stigmergy*, or, more generally, *sematectonic communication* (see Grassé 1959; Bruinsma 1979; Karsai and Pénzes 1993; Bonabeau 1999). This means that the locally defined agents orient themselves not only according to the behavior of a number of neighbours, but also tally traces which the agents place in and read from their environment—like pheromone trails to a food source which produce a positive feedback for following individuals, or of nest structures like honey combs that determine and incite the building of subsequent structures. This distributed organization has been formalized in computer simulation models like *Ant Colony Optimization* (ACO) and initially gave rise to the field of SI (see Bonabeau et al. 1999). In this ABM paradigm, agents collectively transform the incoming information into behavioral patterns and in concrete building structures at the same time.

Here, perception of an environment is transposed from an animal characteristic to an information relation with the aid of a visual interface to make it understandable to the human operator, as media historian Jussi Parikka points out (Parikka 2010: 156). In a seminal publication on SI, Eric Bonabeau, Marco Dorigo and Guy Theraulaz devote a chapter on the computer simulation (CS) of nest building in social wasps. With a three-dimensional Cellular Automaton and carefully evaluated rule sets, they simulated the emergence of a nest architecture which one would find in natural wasps (Bonabeau et al. 1999: 205-252). Stemming from this, computer scientists sought to transform the use of the respective CS technologies from confirming scientific hypotheses to the generative and semi-autonomous development of e.g. *Swarm-driven Idea Models*. Here, the simulation environment works as a virtual testbed for the 'breeding' of complex emergent architectural constructions. In order to result in structures which are somehow suitable for a given architectural problem, the simulators integrate an evolutionary algorithm into the CS which rates the constructional activities of a population of randomly chosen swarms. This consecutively leads to a new population based on the rate-dependent selection of the previous generation of swarms, whilst random changes and recombinations of successful swarms enable the development of unforeseen constructions. In a repetitive process, the CS system yields interesting architectures according to a set of pre-defined evaluation criteria (Mammen and Jacob 2008: 118). Thus, SI enables an integration of architecture into the site-specific environmental context and takes into account aspects of ecological and economic performance of the building (ibid. 2008: 122–124). Whilst one should rather be careful with such tendencies to overemphasize the 'natural integrity' of such outcomes of biologically inspired CS, in terms of a generative approach to the generation of architectural idea models, such *Insect Media* seem to accomplish rather interesting outcomes. However, these are highly dependent on the processually defined boundary conditions of the CS, the design of the learning algorithm which defines the development and 'optimization' of the generation of forms, and not least the expertise of the meta-modeler, the architect.

The second principle in SI is based on the abovementioned movement vectors of flocking individuals defined by local neighbourhoods. Here, the focus lies in the emergence of a dynamic and mutable swarm-space, an intermediate layer between local information processing and collective adaptation to the constantly changing exterior forces of an environmental space. This technique is used for the time-based and dynamic generation of formely unknowable global forms by the non-linear interactions of many mobile individuals. Fueled by sophisticated CGI techniques, ABM softwares were soon embraced by a number of architectural design teams. They transformed creation into merely developing adequate rules which would govern the assembly of components, thus leaving the architect with the role of a meta-designer of self-organizing systems (see e.g. Buus 2006).

Along with other digital techniques such as parametricism (e.g. Schumacher 2009), computational ABM can be networked with digitally controlled production measures. In contrast to traditional building methods, such a 'machine ecology' of file-to-factory mass-cusomization can lead to an endless variety of different building element which are still based on a set of simple rules, and with humans only intervening on a programming meta-level. As an effect, everything is different in absolute size and position, not because of human non-accuracy, but thanks to computational processing of diversity. […] The driving forces to organize the behavior of the control points of the geometry come from both external and internal forces communicating with the evolution of the 3D model (Oosterhuis 2012).

On the one hand, control thereby is handed to the bottom-up self-organization of non-linear agent systems, on the other it is re-introduced by architects and experts who evaluate the generated forms with respect to certain criteria: "With the centrality of population thinking, the emphasis shifted from both individuals and generalized types to the primary of variation and deviation. […D]ifference and process become comprehensible and hence controllable" (Parikka 2010: 167).

Roland Snooks, one of the collaborators in an architectural project called *Kokkugia*, explains how ABM methods deal with explicit architectural problems, and how this differs from many of the earlier approaches to digital architecture. *Kokkugia* has been focused on agent-based methodologies […]. This started as an interest in generative design, not necessarily as a specific interest in computational, algorithmic or scripted work, but as an interest in understanding the emergent nature of public spaces […] of Melbourne and how we could develop emergent methodologies. That led us to develop swarm systems and multi-agent models (see suckerPUNCH 2010).

But this raises the question of how exactly to define the architectural problem. Due to the non-linear relationality (Thacker 2004) of all objects of a public space, the meta-designers seek to describe all sorts of relations of those objects in simple rules. In this way, the micro-relations of individual agent behavior connect with a meso-scale of giving form to single buildings and to a macro-scale of generative urban planning. With ABM software, as Oosterhuis states, such a system will display real time behavior, and the parameters may change continuously over time. The crucial thing is that comprehensiveness only emerges by running the processes. Using the tentative technologies of SI and ABM in generative architecture thus always seems to be a question of how to shape the bottom-up system behaviors with target functions in a gamified trial-and-error process. Otherwise, reasonable results or idea models would merely be a matter of luck (or patience).

> The challenge for the designer is to find those rules that are effective and which are indeed generating complexity. Some design rules produce death, others proliferate life. Some design rules create boring situations, other rules may generate excitement. You can only find the intriguing rules by testing them, by running the process. (Oosterhuis 2006: 25)

Moreover, instead of working with black boxed modules of commercial architecture software like *Rhino*, *Grashopper* or *Processing* with their respective SI *Boid Libraries* or *Plethora* plugins, people like Snooks advocate the development of open source programs, specific to the respective design intention: "[T]he algorithm should emerge from the architectural problem rather than simply the architecture emerging from the algorithm." (suckerPUNCH 2010).

Broadening this understanding, the collaborators of the *Kokkugia* project describe swarm-based urban planning as a simultaneous process of self-organizing agents which would not any longer result in a single optimum solution or master-plan, but in a flexible near-equilibrium, semi-stable state always teetering on the brink of disequilibrium. This allows the system to remain responsive to changing economic, political and social circumstances. (Leach 2009: 61)—or, in other words, it results in an adaptive environment. In addition, the objective to understand urban dynamics by swarm intelligence systems for *Kokkugia* coalesces with generative measures of their non-linear methodologies to produce shapes of buildings and with the ensuing development of novel fabrication techniques. These could lead to a rethinking of tectonics and form on the basis of ABM (suckerPUNCH 2010). As an effect of SI and ABM models with their focus on moving patterns and dynamic flows, the relationship between locally acting autonomous agents and the material composition of architectural buildings and sites can take on novel operational forms.

These computer simulation systems integrate the effects of spacial practices—that is, the agents' movements—in the material urban fabric, and likewise the constraints imposed on those practices by its (computer-simulated) physicality:

> The task of design therefore would be to anticipate what would have evolved over time from the interaction between inhabitants and city. If we adopt the notion of 'scenario planning' that envisages the potential choreographies of use within a particular space in the city, we can see that in effect the task of design is to 'fast forward' that process of evolution, so that we envisage—in the 'future perfect' sense—the way in which the fabric of the city would have evolved in response to the impulses of human habitation (Leach 2009: 62).

SI and ABM thus can be defined as adaptive technologies which facilitate the apprehension of future states of buildings or urban spaces under varying environmental impacts, carrying the potential to deeply change and enhance the procedures of urban planning. One of their main endowments seems to be the procedural production of diversity—in their use as idea models as well as in combination with the possible mass-customization of building parts involved in construction processes which follow from the computational models.

However, at least two factors have to be paid attention to: First, the smoothness with which some of the most popular SI plugins produce ›appealing architectural forms‹ runs the risk of underestimating effects on rather ›trivial‹ considerations of functionality or tectonics of a resulting structure on the part of the meta-designers. In addition to such digital manierism, a second factor has to be be kept in mind: That is, that such processes of scenario building become as well a part of the reality which they try to model. But in contrast to weather simulations, for instance, the modeled systems—that is, maybe the people using an urban plaza—would certainly react to the scenarios produced by urban planning tools of this kind if those would be on display, say, at a community meeting. Such an interaction of the public with computer simulations that *model* this public would likely add a novel layer of unpredictability to the process.

1.4 Regularity

Whereas Beni's and Wang's paper which coined the term SI lead from cellular robotics right into the realm of computational software applications and ABM, another paper from the same year of 1989 proved more visionary with regard to the development of swarm robotics. At MIT Artificial Intelligence Lab, robotics pioneer Rodney Brooks, together with his working group, was searching for an alternative way to achieve intelligent behavior which contested the cognitivist approaches of GOFAI: Brooks believed that only in relation and interaction with the complexities of a surrounding environment, robots would be capable of developing intelligent behavior. The key term was *embeddedness*, and the conceptual principle was *bottom-up*: Knowledge about the world should rather be computed on-the-run by small robots capable of sensing only those conditions of their environment and react accordingly that were needed to fulfil certain tasks—like, moving around—than by complicated robots with complex artificial brains containing large pre-programmed 'concepts' about the surrounding world. And whilst the MIT Lab more and more began to resemble a zoo crowded by small autonomous robot prototypes—the most popular being *Genghis*, a six-legged ›insect‹ robot without based on a 'subsumption architecture' without a central controller that followed swarm principles internally—Brooks together with Anita M. Flynn pictured the future of and a possible field of application for such machines in a paper boldly entitled *Fast, cheap, and out of Control. A Robot Invasion of the Solar System* (1989: 478):

> Complex systems and complex missions take years of planning and force launches to become incredibly expensive. The longer the planning and the more expensive the mission, the more catastrophic if it fails. The solution has always been to plan better, add redundancy, test thoroughly and use high quality components. Based on our experience in building ground based mobile robots (legged and wheeled) we argue here for cheap, fast missions using large numbers of mass produced simple autonomous robots that are small by today's standards (1 to 2 kg). We argue that the time between mission conception and implementation can be radically reduced, that launch mass can be slashed, that totally autonomous robots can be more reliable than ground controlled robots, and that large numbers of robots can change the tradeoff between reliability of individual components and overall mission success. Lastly, we suggest that within a few years it will be possible at modest cost to invade a planet with millions of tiny robots.

This introduction already compiles almost all ingredients that also today make swarm robotics a compelling approach when it comes to coping with complex demands in unpredictable environmental conditions—its greater robustness, flexibility, reliability, and scalability (see also Brooks et al. 1990). Or, simply put: "[U]sing swarms is the same as 'getting a bunch of small cheap dumb things to do the same job as an expensive smart thing'." (Corner and Lamont 2004: 335). And there is also the economic argument: Small robots can be mass-produced, adding economies of scale, and can be largely constructed from off-the-shelf components. Nevertheless, whilst SI and ABM software applications—thanks to rapidly increasing computing power to calculate the interconnected non-linear behavior of large numbers of agents—began to flourish from the 1990s onwards, swarm robot invasions had been a long time coming (Kube and Zhang 1993). It took more than 15 years until Erol Sahin published the seminal volume *Swarm Robotics* (Sahin 2008), with Gerardo Beni authoring an introduction with the title *From Swarm Intelligence to Swarm Robotics* (Beni 2008a) in which he directly addressed this issue:

> [T]he original application of the term [SI] (to robotic systems) did not grow as fast. One of the reasons is that the swarm intelligent robot is really a very advanced machine and the realization of such a system is a distant goal (but still a good research and engineering problem). Meanwhile, it is already very difficult to make small groups of robots do something useful. (ibid. 2008a: 7)

And even if the volume included reports on pioneering projects like *SWARM-BOTS* (Groß et al. 2006) and *I-SWARM* (Seyfried et al. 2005), the featured discourse remained mostly ‘idiosyncratic’: It circled around questions of how to engineer functioning robot collectives in the first place whereas the mentioning of concrete application areas was universally rubricated under ‘future developments’. This time-lag is—apart from the challenges of engineering working physical systems instead of virtual agents—also due to a changing understanding of SI. In 2000, Sanza Kazadi introduced the term *Swarm Engineering* recognizing that—in contrast to the benefits of emergent effects that are used, for instance, in *Kokuggia*’s computational experiments—“the design of predictable, controllable swarms with well-defined global goals and provable minimal conditions” was mandatory in the field of robotics. “To the swarm engineer”, he notes, “the important points in the design of a swarm are that the swarm will do precisely what it is designed to do, and that it will do so reliably and on time.” (Brambilla et al. 2012, 2, cf. Kazadi 2000). The robots’s being out-of-control had to be framed by rigidly determined objectives and behavioral control and—to a comparatively small extend—in some collective robot systems survived in the actual autonomous process of executing the building tasks.

However, the ‘distant goal’ had been approached rather quickly: In the following the research in collective robotics shows a significant take-off, with today leading to about 1,500 hits for ‘swarm robotics’ on the *IEEE Xplore* platform alone. Researchers imagined a whole range of possible applications like collective minesweeping or the distributed monitoring of geographic spaces and eco-systems. Swarming elements were imagined to also take on counter measures by self-assembling into blockings against leakages of hazardous materials, thereby being scalable according to the graveness of a situation. The swarm-bots would synchronize with environmental events in space by tracking, anticipating, and level them by self-formation (see e.g. Beni 2008b).

From around 2005 onwards, some strains of research also developed around the operation of swarm robotics for architectural construction (Saidi et al. 2008; Mammen et al. 2005; Werfel et al. 2006, 2007, 2014; Magnenat et al. 2012; Stroupe et al. 2005; Augugliaro et al. 2013; Mammen et al. 2014; Soleymani et al. 2015; Wawerla et al. 2002; Helm et al. 2012) grounded in the expectation that they not only can […] lead to significant time and cost savings, but their ability to connect digital design data directly to the fabrication process enables the construction of non-standard structures (Willmann et al. 2012: 441).

In addition, at least theoretically, robotic constructive assembly processes are by nature ‘additive’, they are scalable and can incorporate variation in the assembly to accommodate not only economic and programmatic efficiency, but also complex information about individual elements and their position (Willmann et al. 2012: 446).

And finally, swarm robotics have several advantages compared to already existing platforms: First, unlike common robotic building systems which still are centered around human involvement, swarm robotics could be employed in contexts where a direct human involvement is impractical or too dangerous. Second, swarm robotics overcome the stationary method of common robotic building platforms. Unlike the latter, they are not restricted by the size of the platform, which in common systems have a footprint which must be larger than the final structure. And third, a multi-robot assembly makes use of parallelism and offers error tolerance by substitution, as the sub-tasks can be carried out by any robot of the collective (see Petersen 2016).

Recent research efforts in swarm robotics for architectural building can be roughly subdivived in a four-field matrix containing (1) grounded or (2) aerial robots, which use (3) rigid or (4) amorphous building materials. The typical grounded robot is small, lightweight, and manoeuvrable, equipped with sensors that allow for orientation in the environment and for interaction with other robots and with the building material. Basic challenges for operating such systems are e.g. power supply (battery charging periods), mutual collisions or blockages of robots moving around in a given environment, calculation of shortest paths, and reliable mechanisms for identifying, grabbing, and deploying building materials (see Gerling and von Mammen 2016).

State-of-the-art systems like *marXbot* (Bonani et al. 2010), the *SRoCS* Swarm Robotics Construction System (Allwright et al. 2014), or *TERMES* (Werfel et al. 2014) thereby use highly standarized, rigid building material like cubics or—in case of *TERMES*—blocks specifically designed to meet the robots’ manipulators and lifting devices. *TERMES*, which can be perceived as a temporary apex of the scientific field of swarm robotics, is inspired by the decentralized communication structure and collective behavior of termites. The team developed an interaction algorithm for a multi-agent system motivated “by the goal of relatively simple, independent robots with limited capabilities, able to autonomously build a large class of nontrivial structures using a single type of prefabricated building material” (Werfel et al. 2014: 755). After running their algorithm with software agents, the research group implement it in a group of physical robots to test its functioning ‘in vivo’. Quite strikingly, *TERMES* commenced to collectively put together the building bricks. Such blocks—as is referred to also in the other seminal research projects—need the capability to adhere to each other or to be mechanically joint, because the use of a secondary material would further complicate the overall process, whilst the robots respectively employ stigmergy as guidance for the exact positioning of the building elements.

However, there are also approaches, which involve amorphous material. Some researchers experimented with sandbags (Napp et al. 2012), whilst others (Napp and Nagpal 2014; Hunt et al. 2014) used amorphous foam to build ramps in uneven terrains, thereby exploiting an advantage of non-rigid materials: The flexibility and thereby the adaptability of the amorphous material vastly facilitated the construction task in that respective environment, whereas their viscosity and expansion introduced imprecision into the construction process (see Gerling and von Mammen 2016). Gerling and von Mammen thus propose a combined process which involves the spread of amorphous materials to even out irregular terrain and the subsequent use of rigid materials “for precise and swift construction” (ibid.). Although, the latter again poses great challenges when it comes to building up tall structures—in this regard, most systems are limited to the range of their lifting devices. *TERMES* however are able to pile their buildings bricks also to temporary ramps which they are able to climb in order to construct taller structures (Petersen et al. 2011, 2014).

In comparison with grounded robots, aerial robots obviously have more freedom to navigate and—with the nowadays favorably employed quadrocopters—also a high degree of precision. They can work dynamically in three dimensions. Although, where the former are most likely to simply stop and shut down if something interferes with its functioning, the latter run the risk of crashing more easily, and thus need a very accurate control for battery charge. Moreover, they are only fitted to transport relatively light loads, which also affects battery size and thus operation time. This disadvantage also remains present in attempts to increase the versatility of amorphous building material by mixing two-component polyurethane to be ‘printed’ by aerial robots (Hunt et al. 2014).

Nevertheless, UAVs are better suited to build elevated structures (see Gerling and von Mammen 2016; Augugliaro et al. 2013). For instance, the *Aerial Robotics Construction Group* (ARC), a joint research project of two reseach groups at ETH Zurich created a prototype six-meter-tall *Flight Assembled Architecture* tower which contains 1500 foam-brick modules and was assembled by a swarm of autonomous quadrocopters (Willmann et al. 2012: 441-442). As with *TERMES*, the research team emphazised the importance of the ‘nature’ of a suitable building material:

> The payload of flying vehicles is very much limited, whereas materials with high strength and high density favor the use of ARC […]. Consequently, this research focuses on the construction of elements, on lightweight material composites and on complex space frame structures […]. Because the overall shape of these building modules is also determined from aerodynamic considerations, these must be designed according to the specific assembly techniques and building capabilities of the flying machines. The building modules, therefore, must have particular geometrical characteristics so as to meet the required levels of the flying vehicle’s complex aerodynamics, and thus, its building performance. The consequence is a design that is never monotonous or repetitive, but rather specific and adaptable to different architectural and aerial characteristics. […] This ›information‹ logic between dynamic contingencies—such as the requirements of aerial transportation and the physical constraints of production—must be seen as integral. (Willmann et al. 2012: 446-447)

“A design that is never monotonous or repetitive, but rather specific and adaptable”—this perspective certainly can be contradicted. Already the aesthetics of ARC’s prototype flight-assembled brick towers and walls, as well as their *SUPERSTUDIO*-like renderings of future megastructures, both prove different (Willmann et al. 2012: 454). Moreover, in the ARC as well as the TERMES example, the autonomy and the adaptive capacities of the robotic swarm collectives are highly integrated with fitting ‘environmental interfaces’ which on the one hand touch the physicality of the outer environment (e.g. air resistance, irregular surfaces), and on the other the technical specifications of the respective robots (payload, form of building materials, identifiability by building blocks (for instance by RFID tags), sequencing of tasks, etc.). Combined with the necessary reliability in terms of producing satisfying results—that is, the swarm engineering paradigm—it is, as an outcome, little surprising though that most of the contemporary swarm robotic systems—including *TERMES* and *ARC*–execute detailed pre-calculated blueprints. Their adaptivity is the result of a carefully pre-planned system of specifications for standardized building elements.

Thus, statements like the following sound rather lofty if one acknowledges that the respective prototypes still only perform in the artificial environments of laboratories with their radically reduced amount of contingency:

> While it remains to be seen whether ARC will emerge as a viable dynamic building technology, the *Flight Assembled Architecture* prototype successfully illustrates how an ARC approach makes empty airspace tangible to the designer, and addressable by robotic machinery (Willmann et al. 2012: 442).

And furthermore, the abovementioned processes contradict the initial idea of the SI mindset. As swarm robot pioneer Marco Dorigo and his team put it in a paper on their *SRoCS* platform:

> Current implementations of decentralized multi-robot construction systems are limited to the construction of rudimentary structures such as walls and clusters, or rely on the use of a blueprint or external infrastructure for positioning and communication. In unknown environments, the use of blueprints is unattractive as it cannot adapt to the heterogeneities in the environment, such as irregular terrain. Furthermore, the reliance on external infrastructure is also unattractive, as it is unsuitable for rapid deployment in unknown environments. (Allwright et al. 2014: 167)

Their *Swarm Robotics Construction System* avoids the use of a blueprint by enabling the robots to adapt their positioning on visual clues from the environment alone—for instance, they independently identify obstacles or irregularities—and from the building elements which are equipped with 2D bar codes and different lights that indicate their respective status. After positioning the building blocks the robots update the colors of the LEDs on the blocks. Depending on the algorithm in use, these colors can be assigned various meanings, e.g. a particular color can be used to indicate a seed block or a block that has already been placed into the structure, thereby developing the stigmergic building process (see Allwright et al. 2014: 163).

However, in contrast with the sophistication of architectural design and possible mass customization procedures enabled by computational SI application, the physical implementation of collective building processes in swarm robot systems until today remains rather clumsy. Instead of a massively increasing variation of building elements stemming from emergence- and complexity-prone design processes which integrate and calculate a large number of possible agent behaviors, environmental forces, and random fluctiations, swarm robotics is based on careful preparation and pre-planning which—for the most part—eliminates contingency. Working with highly standardized elements and in almost all cases with blueprints or central planning modules, it dimishes the vivid secondary adaptive environments of the computational approaches to mere basic functions, like preventing robots to crash. Hence, the already non-trivial task of constructing reliably functioning robot collectives of larger sizes—see Harvard University's *KILOBOT*-project as a pivotal example which is composed of a stunning 1000 individual robots but comes with a no less dazzlingly slow speed of (re-)arranging collectively (Rubenstein et al. 2012)—is multiplied when it comes to use them as useful construction platform.

For the time being, and compared to already existing (robotic) technologies in architecture, swarm robotics seems to involve rather too much restrictions and disadvantages—for instance in terms of aesthetically and conceptually sophisticated architectural results—and seems to offer rather too few advantages—like being able to autonomously explore terrains and environments which are inaccessible for humans. It is therefore not a coincidence that the *SRoCS* paper leads back to the beginning. Contemplating its possible application area, it is straightforwardly echoing Rodney Brooks's 25-year old vision:

> It is possible that a multi-robot construction system will be a practical solution in the future for building basic infrastructure, such as shelter, rail, and power distribution networks on extraterrestrial planets or moons, prior to the arrival of humans. (Allwright et al. 2014: 158; see also Khoshnevis 2004).

1.5 Conclusion

The chapter demonstrated that swarm intelligence and swarm robotics can be perceived as exemplary adaptive environments. Both approach complex assembling problems by means of self-organizing processes of artificial *populations* of individual agents and their interactional behavior in time. SI and SR thus substitute geometric principles by 'visions of process' as generative forces for architectural design and construction. The emergent and adaptive capacities of swarms on the collective level can be regarded as a mediating layer between exterior influences from the physical environment and the individual actions of swarm members. Understood as a 'secondary environment', swarm systems hence offer multiple benefits for architectural design and construction: First, its mindset integrates the levels of individual movements of particles (simulated humans, traffic flows, winds, etc.) at the mesoscale of single buildings and at the global level of urbanscapes; second, with the capability of rapidly generating diverse scenarios, they can serve as idea generators in the design and construction process; third, this also leads to the integration of futurologic aspects to the design process since computer experiments can direct to previously unknown but desirable outcomes; fourth, such ideas can literally materialize by combining SI design applications with rapid prototyping and mass customization strategies; fifth, such applications can also integrate e.g. customer feedback and can lead to seemless feedback loops over the entire design process; and last but not least, with SR the prospect of translating such autonomy, flexibility and dynamism to architectural construction is substantiated. In a threefold way, the chapter explored the technological history of SI and SR as well as present applications. It thereby discussed in which ways and in which contexts the abovementioned potentials are already utilized.

The first section situated SI and SR as a peculiar form of adaptive environment on a broader conceptual plane which nicely connects the currently burgeoning media-cultural discourse of ‘media ecologies’ and *environmentality* with the more application-oriented approaches to adaptive environments in architecture. It thereby provided some historical traces of the conceptual transformation from biological and ecological backgrounds to technical environments whose understanding seems mandatory for a comprehensive account of the term ‘adaptive environment’.

The second section provided a critical overview of a number of seminal computational approaches to architecture which derive from the SI mindset and which make use of the adaptability of self-organizing computational agents. By distinguishing approaches to self-organization which are oriented at social insects from those which simulate flocks or schools on the move, it also discussed the transformation of the role of the architect into a meta-designer: Using the tentative technologies of SI and ABM in generative architecture thus always seems to be a question of how to shape the bottom-up system behaviors with target functions in a gamified trial-and-error process. One of their main endowments is the procedural production of *diversity*—in their use as idea models as well as in combination with the possible mass-customization of building parts involved in construction processes which follow from the computational models.

And finally, the third section differentiated current developments in SR for architectural building in a four-field matrix of (1) grounded or (2) aerial robots, which use (3) rigid or (4) amorphous building materials. It focused on three state-of-the art projects, namely the *TERMES* robotic building system of Harvard University, the *SRoCS* Swarm Robotic Construction System, and the *ARC* Aerial Robotics Construction Group of ETH Zurich, and discussed their particular layout and their performance achievements and difficulties. This analysis showed that, unlike SI in architectural design, SR in architectural construction is based on careful preparation and preplanning which—for the most part—eliminates contingency. Working with highly standardized elements and in almost all cases with blueprints or central planning modules, the secondary adaptive environments of the computational approaches is diminished to mere basic functions—like preventing robots to collide. The question remains whether such robotic building technologies continue to be a highly specialized field for extreme physical environments, which are unsuitable or intractable for traditional methods, or whether they can follow an optimistic ‘vision of process’ and proliferate into buzzing swarms of rigorous mobile 3D-printers—a vision which would truly be revolutionary for building processes.

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References

Agrawal A (2005) Environmentality: technologies of government and the making of subjects. New ecologies for the twenty-first century. Duke University Press, Durham

Allwright M, Bhalla N, El.faham H, Pinciroli C, Anthoun A, Dorigo M (2014) SRoCS: leveraging stigmergy on a multi-robot construction platform for unknown environments, 158–169. In: Dorigo M (ed) Swarm intelligence: 9th international conference, ANTS 2014, Brussels, Belgium, September 10–12, 2014; Proceedings. Lecture Notes in Computer Science, 8667. Springer, Berlin

Augugliaro F, Mirjan A, Gramazio F, Kohler M (2013) Building tensile structures with flying machines. In: IEEE/RSJ international conference on intelligent robots and systems, (IROS) Tokyo, November 3–7, 2013). IEEE, pp 3487–3492

Baecker D (1990) Die Dekonstruktion der Schachtel. Innen und Außen in der Architektur. In Unbeobachtete Welt. Über Kunst und Architektur, ed. by Niklas Luhmann, Frederick D. Bunsen, Dirk Baecker, 83. Haux, Bielefeld

Banham R (1969) The architecture of the well-tempered environment. University of Chicago Press, Chicago

Beni G, Wang J (1993) Swarm intelligence in cellular robotic systems. In: Dario P, Sandini G, Aebischer P (eds) Robots and biological systems: towards a new bionics?. Berlin, Heidelberg: Springer Berlin Heidelberg, 703–12, https://doi.org/10.1007/978-3-642-58069-7_38

Beni G (2008a) From swarm intelligence to swarm robotics. In: Sahin E, Spears WM (eds) Swarm robotics. Springer, New York, pp 3–9

Beni G (2008b) Order by disordered action in swarms. In: Sahin E, Spears WM (eds) Swarm Robotics. Springer, New York, pp 153–172

Bonabeau E (1999) Artificial life 5, 2, Special Issue: Stigmergy

Bonabeau E, Dorigo M, Theraulaz G (1999) Swarm intelligence. From natural to artificial systems. Oxford University Press, New York

Bonani M, Longchamp V, Magnenat S, Rétornaz P, Burnier D, Roulet G, Vaussard F, Bleuler H, Mondada F (2010) The marXbot, a miniature mobile robot opening new perspectives for the collective-robotic research. In: 2010 IEEE/RSJ international conference on intelligent robots and systems, 4187–93, https://doi.org/10.1109/IROS.2010.5649153

Brambilla M, Ferrante E, Birattari M, Dorigo M (2012) Swarm robotics. A review from the swarm engineering perspective. IRIDIA Technical Report No. TR/IRIDIA/2012–014

Brooks RA, Maes P, Mataric MJ, More G (1990) Lunar base construction robots. In: Proceedings IROS'90. IEEE international workshop on intelligent robots and systems' 90. Towards a new frontier of applications. IEEE, 389–392

Brooks RA, Flynn AM (1989) Fast, cheap, and out of control: a robot invasion of the solar system. J Br Interplanet Soc 42:478–485

Bruinsma OH (1979) An analysis of building behaviour of the termite Macrotermes Subhyalinus, Rambur (PhD thesis). Wageningen: Landbouwhoge School, The Netherlands

Brynjolfsson E, McAfee A (2016) The second machine age. work, progress, and prosperity in a time of brilliant technologies.W. W. Norton, New York, London

Buus DP (2006) Constructing human-like architecture with swarm intelligence, http://projekter.aau.dk/projekter/en/studentthesis/constructing-humanlike-architecture-with-swarm-intelligence. Accessed 21 Sept 2017

Corner JJ, Lamont GB Parallel simulation of UAV swarm scenarios. In: Ingalls RG, Rossetti MD, Smith JS, Peters BA (eds) Proceedings of the 2004 winter simulation conference, December 5–8th, 355–363. Winter Simulation Conference Board of Directors

Ford M (2016) The rise of the robots: technology and the threat of mass unenployment. Oneworld, London

Foucault M (2004) Naissance de la biopolitique. Cours au Collège de France (1978–1979). Gallimard, Paris

Friedrich C (2009) Space queries design toolset. Pointcloud-based multi-directional real-time Swarm Architecture design exploration. In: 2009 15th international conference on virtual systems and multimedia: proceedings: VSMM 2009 9–12 September 2009 Vienna. Austria, ed. International Conference on Virtual Systems and MultiMedia. IEEE Computer Society, Los Alamitos, Calif, pp 174–178

Fuller M (2005) Media ecologies. MIT Press, Cambridge

Gabrys J (2007) Automatic sensation: environmental sensors in the digital city. Senses Soc 2(2):189–200

Gabrys J (2016) Program earth. University of Minnesota Press, Minneapolis

Gerling V, von Mammen S (2016) Robotics for self-organised construction. In: 1st international workshop on foundations and applications of Self*Systems (FAS*W). IEEE, 162–167, http://ieeexplore.ieee.org/document/7789462/

Grassé P-P (1959) La reconstruction du nid et les coordinations inter-individuelles chez Bellicositermes natalensis et Cubitermes sp. La théorie de la stigmergie: Essai d'interprétation du comportement des Termites constructeurs. In Insectes Sociaux 6:41–83

Groß R, Bonani M, Mondada F, Dorigo M (2006) Autonomous self-assembly in swarm-bots. IEEE Trans Rob 22(6):1115–1130

Halpern O, LeCavalier J, Calvillo N, Pietsch W (2013) Test-bed urbanism. Public Culture 25(2):272–306

Hansen Mark B N (2014) Feed-forward: on the future of twenty-first-century media. Chicago University Press, Chicago

Hartkopf V, Loftness V, Mahdavi A, Lee S, Shankavaram J (1997) An integrated approach to design and engineering of intelligent buildings—the intelligent workplace at carnegie mellon university. Autom Constr. https://doi.org/10.1016/S0926-5805(97)00019-8

Helm V, Ercan S, Gramazio F, Kohler M (2012) Mobile robotic fabrication on construction sites: DimRob. In: IEEE/RSJ international conference on intelligent robots and systems. IEEE

Hörl E, Burton J (ed) (2017) General ecology: the new ecological paradigm. Theory. Bloomsbury, Bloomsbury Academic, London, Oxford, New York, New Delhi, Sydney

Hunt G, Mitzalis F, Alhinai T, Hooper PA, Kovac M (2014) 3D printing with flying robots. In: IEEE international conference on robotics and automation (ICRA). IEEE, pp 4493–4499

Karsai I, Pénzes Z (1993) Comb building in social wasps: self-organization and stigmergic script. J Theor Biol 161(4):505–525

Kazadi ST (2000) Swarm engineering. Dissertation (PhD), California Institute of Technology

Kelly K (1994) Out of control: the new biology of machines, social systems, and the economic world. Addison-Wesley, Reading, Mass

Kennedy J, Eberhart RC (1995) Particle swarm optimization. In: Proceedings of the IEEE international conference on neural networks. IEEE Service Center, Piscataway, pp 1942–1948

Khoshnevis B (2004) Automated construction by contour crafting—related robotics and information technologies. Autom Constr 13(1):5–19

Kitchin R, McArdle G, Lauriault T (eds) (2017) Data and the city. Routledge, London

Kokuggia (2010) Stigmergic landscape, http://www.kokkugia.com/stigmergic-landscape. Accessed 23 Oct 2017

Kube C Ronald, Zhang H (1993) Collective robotics: from social insects to robots. Adapt Behav 2(2):189–219

Laboratory for Visionary Architecture (2014) Philips Light + Building Pavilion, https://www.l-a-v-a.net/projects/philips-light-building-pavilion-2/. Accessed 23 Oct 2017

Leach N (2009) Swarm urbanism. Architect Des 79:56–63

Löffler P, Sprenger F (ed) (2016) Schwerpunkt Medienökologien. Zeitschrift für Medienwissenschaft, 14

Magnenat S, Philippsen R, Mondada F (2012) Autonomous construction using scarce resources in unknown environments. Autonom Robots 33

von Mammen S, Jacob C, Kókai G (2005) Evolving swarms that build 3d structures. In: CEC 2005, IEEE congress on evolutionary computation. IEEE Press, Edinburgh, 1434–1441. UK

von Mammen S, Jacob C (2008) Swarm-driven idea models—from insect nests to modern architecture. WIT Trans Ecology Environ 113, 117–26 von Mammen S, Tomforde S, Höhner J, Lehner P, Förschner L, Hiemer A, Nicola M, Blickling P (2014) Ocbotics: an organic computing approach to collaborative robotic swarms. In: 2014 IEEE symposium on swarm intelligence. IEEE, pp 1–8

McLuhan M (2001) War and peace in the global village. Gingko Press, Corte Madera, pp 174–190

Napp N, Rappoli OR, Wu JM, Nagpal R (2012) Materials and mechanisms for amorphous robotic construction. In: IEEE/RSJ international conference on intelligent robots and systems. IEEE, pp 4879–4885

Napp N, Nagpal R (2014) Distributed amorphous ramp construction in unstructured environments. Robotica 32(2):279–290

Oosterhuis K (2006) Swarm architecture II. In: Oosterhuis K, Feireiss L (eds) Game, set and match II, On computer games, advanced geometries, and digital technologies. Episode, Rotterdam, pp 14–28

Oosterhuis K (2012) Simply complex, toward a new kind of building. Front Architect Res 1(4): 411–20, https://doi.org/10.1016/j.foar.2012.08.003

Parikka J (2010) Insect media. University of Minnesota Press, Minneapolis

Parisi L (2013) Contagious architecture. MIT Press, Cambridge

Petersen K, Nagpal R, Werfel J (2011) TERMES: an autonomous robotic system for three-dimensional collective construction. In: Durrant-Whyte HF et al (eds) Robotics: science and systems VII. MIT Press, Cambridge, pp 257–264

Petersen K (2016) Collective construction by termite-inspired robots (PhD thesis, 2014). Harvard University, https://dash.harvard.edu/bitstream/handle/1/13068244/Petersen_gsas.harvard.inactive_0084L_11836.pdf?sequence=1. Accessed 28 Nov 2016

Reynolds CW (1987) Flocks, herds, and schools: a distributed behavioral model. Comput Graph 21(4):25–34

Rubenstein M, Ahler C, Nagpal R (2012) Kilobot: a low cost scalable robot system for collective behaviors. In Proceedings of 2012 IEEE international conference on robotics and automation (IRCA 2012). Computer Society Press of the IEEE, Washington, DC

Sahin E (2008) Swarm robotics: from sources of inspiration to domains of application. In: Sahin E, Spears WM (eds) Swarm robotics. Springer, New York, pp 10–20

Saidi KS, O'Brien JB, Lytle AM (2008) Robotics in construction. In: Springer handbook of robotics. Springer, Berlin Heidelberg, pp 1079–1099

Schumacher P (2009) Parametricism: a new global style for architecture and urban design. In: Architectural design 79—Digital Cities, pp 14–23

Seyfried J, Szymanski M, Bender N, Estaña R, Thiel M, Wörn H (2005) The I-SWARM project: intelligent small world autonomous robots for micro-manipulation. In: Şahin E, Spears, WM (eds) Swarm robotics: SAB 2004 international workshop, Santa Monica, CA, USA, July 17, 2004, Revised Selected Papers. Springer, Berlin, Heidelberg, pp 70–83

Soleymani T, Trianni V, Bonani M, Mondada F, Dorigo M (2015) Autonomous construction with compliant building material. In: Advances in intelligent systems and computing 2015. Springer

Sprenger F (2015) Architekturen des environments—Reyner Banham und das Dritte Maschinenzeitalter. In Zeitschrift für Medienwissenschaft 12, 55–67

Sprenger F (2018) (forthcoming) Epistemologien des Umgebens

Sprenger F (2014) Zwischen Umwelt und Milieu—Zur Begriffsgeschichte von Environment in der Evolutionstheorie. In Forum Interdisziplinäre Begriffsgeschichte 3(2)

Starr SL (1995) Ecologies of knowledge: work and politics in science and techology. SUNY Press, Albany

Stroupe A, Huntsberger T, Okon A, Aghazarian H, Robinson M (2005) Behavior-based multi-robot collaboration for autonomous construction tasks. In: 2005 IEEE/RSJ international conference on intelligent robots and systems. IEEE, pp 1495–1500

suckerPUNCH (2010) Interview with roland snooks. 2010 (April 25), http://www.suckerpunchdaily.com/2010/04/25/interview-with-roland-snooks/. Accessed 21 Sept 2017

Thacker, Eugene. 2004. Networks, Swarms, Multitudes. In *CTheory*. http://www.ctheory.net/articles.aspx?id=423. Accessed 21 Sept 2017

Thrift N (2007) From born to made: technology, biology and space. In: Thrift N (ed) Non-representational theory. Routledge, London, New York, pp 153–170

Thrift N (2014) The 'Sentient' city and what it may portend. Big Data Soc 1(1):1–21

Vehlken S (2013) Zootechnologies. Swarming as a cultural technique. Theor Cultu Soc 30(6):110–131

Wawerla J, Sukhatme GS, Mataric MJ (2002) Collective construction with multiple robots. In: IEEE/RSJ international conference on intelligent robots and systems (IROS 2002). IEEE, pp 2696–2701

Wiesenhuetter S, Wilde A, Noenning JR (2016) Swarm intelligence in architectural design. In ICSI 2016: advances in swarm intelligence, pp 3–13

Weiser M (1991) The computer for the 21st century. Sci Am 265(3):94–104

Werfel J, Ingber D, Nagpal R (2007) Collective construction of environmentally-adaptive structures. In: IEEE/RSJ international conference on intelligent robots and systems. IEEE, pp 2345–2352

Werfel J, Bar-Yam Y, RusD, Nagpal R (2006) Distributed construction by mobile robots with enhanced building blocks. In Proceedings 2006 IEEE international conference on robotics and automation, 2006. ICRA 2006. Los Alamitos: IEEE Computer Society Press, pp 2787–2794

Werfel J, Petersen K, Nagpal R (2014) Designing collective behavior in a termite-inspired robot construction team. Science 343(6172):754–758

Willmann J et al (2012) Aerial robotic construction towards a new field of architectural research. Int J Architect Comput 10(3):439–459