Springer Series in Adaptive Environments

Henriette Bier
Editor

Robotic Building

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Preface

While architecture and architectural production is increasingly incorporating aspects of non-human agency employing data, information and knowledge contained within the (worldwide) network connecting electronic devices, the relevant question for the future is not if but how robotic systems will be incorporated into building processes and physically built environments (Bier 2013) in order to improve everyday life. The first book of the Adaptive Environments (AE) series on Robotic Building (RB) aims to answer this question by critically reflecting on the achievements of the last decades in the application of robotics in architecture and furthermore outlining potential future developments and their societal implications. The focus is on robotic systems embedded in buildings and building processes implying that architecture is enabled to interact with its users and surroundings in real time and corresponding Design-to-Production and -Operation (D2P&O) chains are (in part or as whole) robotically driven.

Such modes of production and operation involve agency of both humans and non-humans. Thus, agency is not located in one or another but in the heterogeneous associations between them (Bier 2016), and authorship is neither human nor non-human but collective, hybrid and distributed (Latour 2014).

Robotic Building (RB) as investigated in this AE volume relies on interactions between human and non-human agents not only at design and production level but also at building operation level, wherein users and environmental conditions contribute to the emergence of multiple architectural configurations. In this context, design becomes process—instead of object-oriented—use of space becomes time—instead of program- or function-based—which implies that architects' design increasingly processes, while users operate multiple time-based architectural configurations emerging from the same physical space that may physically or sensorially reconfigure in accordance with the environmental- and user-specific needs. If spatial reconfiguration may be facilitating multiple, changing uses of physically built space within reduced timeframes, interactive energy and climate control systems embedded in building components and employing renewable energy sources, such as solar and wind power, may reduce architecture's ecological footprint while enabling a time-based, demand-driven use of space. Both rely on virtual modelling and simulation interfacing the production and real-time operation of physically built space (Latour 2014) establishing thereby an unprecedented Design-to-Robotic-Production and -Operation (D2RP&O) feedback loop, which is a focus of this book.

The integration of D2RP with D2RO implies understanding both approaches as requiring safe human–robot interaction and collaboration in the production and operation of buildings. Since both production and operation of buildings take place in more or less unstructured environments, both imply similar challenges and opportunities. RB links, therefore, design and production with smart operation of the built environment and advances applications in performance optimization, robotic manufacturing and user-driven building operation.

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The first volume of Springer's Adaptive Environments book series has profited from the Robotic Building session at the Game Set Match #3 symposium organized at TU Delft (2016). It builds up on the abstracts presented at this session, which were published in Spool's first issue on Cyber-physical Architecture (2017). It has profited from the contribution of reviewers, who have single-blind reviewed each chapter. In particular, the contribution of the editors-in-chief Holger Schnädelbach and Kristof Van Laerhoven and of the editorial board Keith Green (Cornell University, USA), Justin Dirrenberger (CNAM, France), Sebastian Vehlken (Leuphana University, Germany), Jean Vanderdonkt (Université catholique de Louvain, Belgium), Mikael Wiberg (Umeå University, Sweden), Omar Khan (Buffalo University, USA), Marcus Foth (Queensland University of Technology, Australia), Ava Fatah (University College London, UK), Martin Knöll (Technical University Darmstadt, Germany), Gerd Kortuem (Technical University Delft, Netherlands), Hedda Schmidtke (University of Oregon, USA), Norbert Streitz (Smart Future Initiative, Germany), David Gerber (Arup Research, UK) and (Philippe Morel, ENSAPM, France) needs to be acknowledged. Furthermore, the contribution of Senatore Gennaro (EPFL, Switzerland), Kevin Clement (Kengo Kuma and Associates, Japan), Tapio Heikkilä (VTT, Finland), Christian Karl (University Duisburg, Germany) and from Springer's side Beverley Ford (Springer Computer Science, UK) and Nancy Wade-Jones (Springer Nature, UK) requires additional acknowledgement.

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Editor and Contributors

About the Editor

Henriette Bier graduated (1989) from the University of Karlsruhe in Germany. She worked with Morphosis (1999–2001) on internationally relevant projects in the USA and Europe. She has taught computational design (2002–2003) at universities in Italy, Austria, Germany, Belgium and the Netherlands. Since 2004, she has been teaching and researching as a Ph.D. researcher and later on as Assistant and Associate Professor at the Technical University Delft (TUD) with a focus on application of robotics in architecture. In 2017, she was appointed Professor at Dessau Institute of Architecture in Germany.

From 2005–06, she initiated and coordinated the workshop and lecture series on Digital Design and Fabrication with invited guests from MIT and ETHZ. Since 2006, she co-developed the education and research frameworks for Non-standard and Interactive Architecture at Hyperbody and Border Conditions at Public Building, TU Delft. Since 2014, she has been leading the Architecture M.Sc. specialization with a focus on robotics in architecture, covering 9 courses of 80 ECTS offered to about 70 students per year. She co-tutored more than 100 graduation projects from which several have received Archiprix nominations, mentions and prizes with the most prestigious one being the 1st International Archiprix prize in 2015. Her graduates successfully practice architecture in internationally known offices (such as Foster, Hadid, UN Studio, OMA) and implement research at relevant institutions (such as TUD, ETHZ, US).

In 2008, she finalized her Ph.D. on System-embedded Intelligence in Architecture, and coordinated until 2010 two EU-funded projects focusing on F2F and online postgraduate education. In 2010, she started developing the academic education and research framework for Robotic Building (RB). In 2011, she joined Delft Robotics Institute (DRI), and in 2013 she received 4TU funding, which allowed her to set up the first robotic laboratory in the faculty of Architecture and the Built Environment, TU Delft, with a team of six researchers. In 2016, she received again 4TU funding and together with funding from the industry she secured 2017 an additional position for a Ph.D. student working on multi-material robotic 3D printing.

She is a member of the M.Sc. admissions committee since 2013 and was research coordinator of the Architectural Engineering and Technology (AET) department from 2014–16. In this role, she has been leading the development of the online Wiki platform to support the AE&T research. She has been a member of several Ph.D. admission committees and is now chairing the Ph.D. admissions committee of AET.

Results of her research are published internationally in more than 120 journals, books and exhibits. Her media appearances such as the TEDx held in Delft 2015 and her participation in exhibits such as Imprimer le Monde at Centre Pompidou in Paris 2017 ensure dissemination of her research to larger audiences. She is a member of several editorial boards and scientific committees and co-organized conferences and co-edited several books and journal issues on data-driven design and robotics in architecture. Most recently, she co-founded the International Association Adaptive Environments with its publication platform in the Springer book series Adaptive Environments.

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Abstract

The first volume of the Adaptive Environments Springer book series focuses on *Robotic Building*, which refers to both physically built robotic environments and robotically supported building processes. Physically built robotic environments consist of reconfigurable, adaptive systems incorporating sensor–actuator mechanisms that enable buildings to interact with their users and surroundings in real time. These require Design-to-Production and -Operation chains that are numerically controlled and (partially or completely) robotically driven. From architectured materials, on- and off-site robotic production to Robotic Building operation augmenting everyday life, the volume examines achievements of the last decades and outlines potential future developments in Robotic Building.

Keywords Architecture · Adaptation · Reconfiguration · Robotic Building
Design-to-Robotic-Production · Design-to-Robotic-Operation

Introduction

The first book of Springer's Adaptive Environments (AE) book series aims to answer the question of how robotic systems are incorporated into building processes and physically built environments (Bier 2013) in order to improve building production and operation processes by critically reflecting on the achievements of the last decades and furthermore outline potential future developments and their societal implications. The focus is on robotic systems embedded in buildings and building processes implying that architecture is enabled to interact with its users and surroundings in real time, and corresponding Design-to-Production and -Operation (D2P&O) chains are (in part or as whole) robotically driven (Bier 2017).

Robotic Building (RB) as investigated in this first AE volume relies on interactions between human and non-human agents at design, production and building operation level. The latter implies that users and environmental conditions contribute to the emergence of various architectural configurations. These changing configurations allow spaces to adapt to variations in occupancy and use, climate needs, etc. They rely on virtual modelling and simulation interfacing the production and real-time operation of physically built space establishing thereby an unprecedented Design-to-Robotic-Production and -Operation (D2RP&O) feedback loop, which is a focus of this book (Bier 2017; Bier and Knight 2014).

The chapters of the first volume of the Adaptive Environments Springer book series address the D2RP and D2RO aspects from various perspectives. For instance, *robot–robot interaction* and *human–robot collaboration* are investigated with respect to their potential to improve productivity, while *robotics embedded in built structures* is explored from the perspective of adaptation to structural, environmental or functional requirements. Materials are discussed from the perspective of *smart and architectured materials* as approaches to work with even design material properties in order to efficiently produce and operate buildings.

Sebastian Vehlken discusses and reviews in Chap. 1 the application of swarm intelligence (SI) and swarm robotics (SR) to architecture and building construction from a history of science and technology perspective. He explores the conceptual entanglements of swarm intelligence and provides a critical overview of seminal SI approaches in architectural design. SR is investigated mainly from the perspective of *robot–robot interaction* and its potential for construction processes. From an applied science perspective, Timo Salmi et al. present in Chap. 2 *human–robot collaboration*. Safety and control technologies of human–robot collaboration are outlined, and sensor-assisted control approaches for industrial robots are described in detail. Furthermore, applicability of sensor-based robotics and potential of robotics in building construction in general are also evaluated. Chap. 3 focuses on reexamining and exploring through history, thus precedents, and case studies the relevance and potential of *intertwining human and non-human agents* in architectural production.

Chapter 4 by Justin Dirrenberger explores *architectured materials* as bridging across the micro-scale of materials to the macro-scale of architectural structures, with the ultimate goal to implement large-scale *robotic additive manufacturing* at building scale. Robotic additive manufacturing is addressed in the next chapter as well but more from the perspective of its potential to complement other *robotic building* techniques required in the production and operation of buildings. Henriette Bier et al. explore challenges and opportunities of integrating the two into a chained D2RP&O process.

D2RO is furthermore explored in Chap. 6 authored by Keith Green, who argues that by *embedding robotics in buildings* interactive and therefore intimate relationships between physical environments and humans are forged. These rely, according to Holger Schnädelbach, on feedback loops between humans and environment that shape such interactions. He examines in the next chapter human–machine interaction and requirements for *adaptive architecture*. In terms of their efficiency, Senatore Gennaro identifies a design approach for *adaptive structures* that is using a strategically integrated actuation system, which redirects the internal load path to homogenize the stresses and to keep deflections within limits by changing the shape of the structure. In contrast, Doris Sung identifies *passive–active systems* as reasonable alternative and complement to the growing number of active systems that are imbued with artificial intelligence.

The chapters of the first volume of the Adaptive Environments Springer book series present theoretical and applied research on robotics in architecture and building construction, identifying its challenges and opportunities. Main consideration is that production and operation of buildings are in the future robotized. Thus understanding that certain skills sets are better acquired and executed by humans while others by machines is understood as key to developing future interaction scenarios between humans and robots. The goal is to take advantage of robotics when it comes to heavy work, precision, repeatability, etc., while still relying on human common sense, creativity, decision-making, etc. The expectation is that in future, interaction between robots and humans at building production and operation level will increase and diversify, with robots becoming more autonomous and human–robot teams collaboratively sharing control. These interactions are *adaptive* in that the individual and collective behaviours reconfigure according to the changing environment.

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

Sebastian Vehlken

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

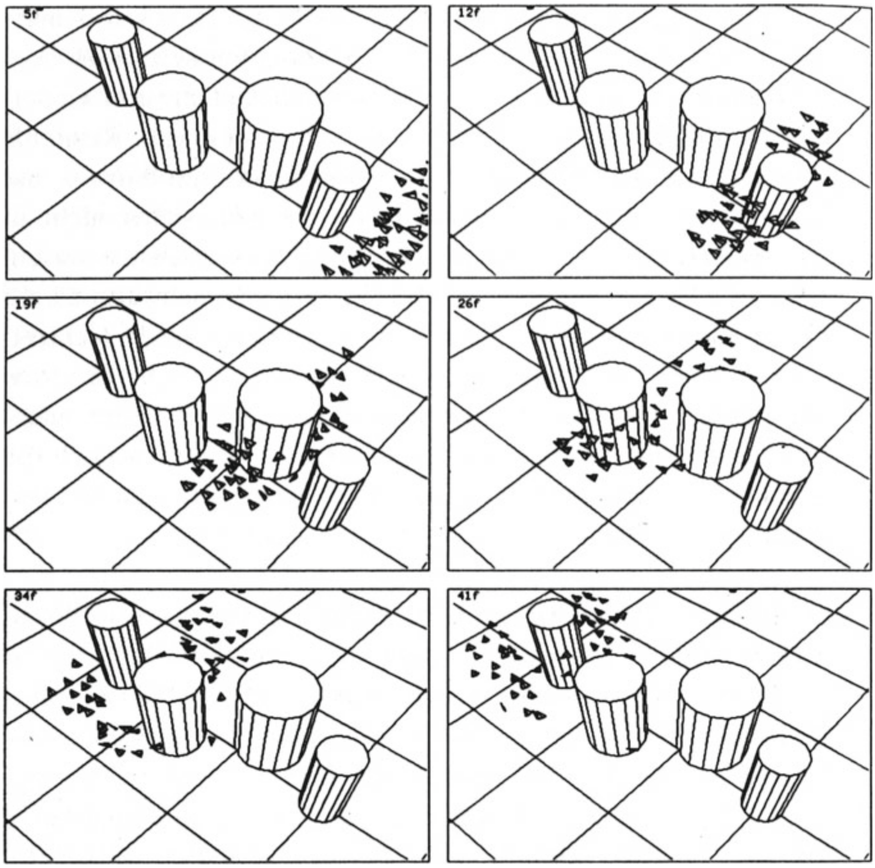

Fig. 1.1 In 1986, computer graphics designer Craig Reynolds developed a pioneering SI application known as the Boids Simulation. Its 'bird-oid' agents show self-organized collective movement based on a flocking algorithm of only three basic behaviors in local neighborhoods: Separation (steer to avoid 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