# Swarm Robotics, or: The Smartness of 'a bunch of cheap dumb things'

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## Abstract

Not only recent Science Fiction – e.g., Star Trek Beyond (USA 2016) – celebrates the capacities of robot collectives. Also RoboCup, an annual robot soccer competition, or Harvard University's Kilobot Project show stunning examples of the central idea behind Swarm Robotics: »[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« (Beni/Wang 1989). This article examines some crucial aspects of the techno-history of a research field which intertwines engineering and biological knowledge and whose applications deal with compelling questions about synchronization and self-organization in changing environments – on the ground, in the air, and under water. Swarm Robotics, I argue, thereby challenge traditional architectural concepts by exhibiting a thorough »vision of process« (Gramazio/Kohler et al. 2013).

## Keywords

Swarm robotics; Swarm Intelligence (SI); agent-based modeling (ABM); architectural design

# 1 Going wild

Swarming, as I have argued elsewhere[1], can be understood as a novel cultural technique: 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, swarms inspired agent-based modelling and simulation (ABM), which in turn provided biology researchers with enduring knowledge about 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 – from epidemiology to logistics, from market simulations to crowd control. Swarm intelligence (SI) has thus become a fundamental cultural technique for governing dynamic processes.

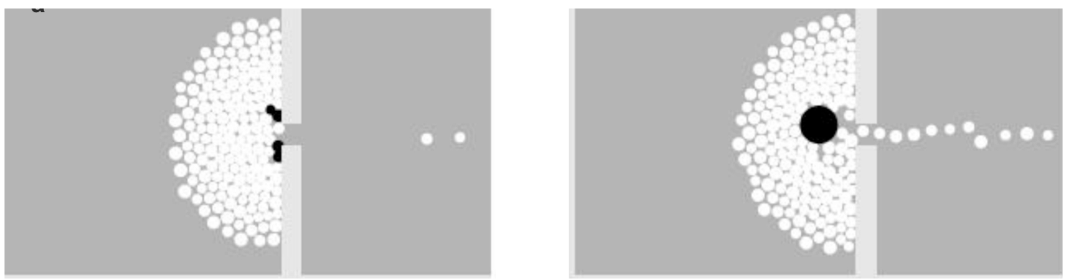

FIGURE 1 Dirk Helbing, Imre Farkas, and Tamás Vicsek, 'Simulation dynamical features of escape panic', in Nature 407 (2000), 487-490: 488.

This capacity also appeals to architectural and building processes. The application of ABM, for instance, proved effective in evacuation studies. Computer simulations of the collective movement of agents in 3D-space can reveal counter-intuitive solutions for architectures which smoothen the flow and increase the speed of movement – like placing pillars directly in front of an exit. In such cases, swarming affects the *inner structure* of a building.[2] (Fig. 1) In urban planning, the simulation of traffic or pedestrians flows and patterns has been used to also shape the *outer appearance* of buildings and public spaces. As an example, the experimental architecture research practice Kokkugia modelled force fields of the dynamic surroundings of buildings in a city scape by means of point clouds or used SI models which are inspired by termites for the optimization of routing by simulated pheromone trails.[3] (Fig. 2)

1 Sebastian Vehlken, 'Zootechnologies. Swarming as a Cultural Technique', *Theory, Culture and Society* 30/6, *Special issue Cultural Techniques* (2013): 110-131.

2 Compare e.g. Dirk Helbing and Anders Johansson, 'Pedestrian, Crowd and Evacuation Dynamics,' in *Encyclopedia of Complexity and Systems Science*, ed. Robert A. Meyers, (New York: Springer, 2009), 6476-6495; Dirk Helbing et. al., 'Self-organized pedestrian crowd dynamics: Experiments, simulations, and design solution,' *Transp Sci* 39(1) (2005):1–24.

3 See: 'Interview with Roland Snooks,' *suckerPUNCH*, April 25, 2010, accessed November 28, 2016, http://www.suckerpunchdaily.com/2010/04/25/interview-with-roland-snooks/. In *Emergent Field* (2003), Kokkugia uses the example of a plaza around Melbourne's Nauru House: the project attempts to develop an emergent form of urban space in a critique of the modernist object-ground relationship. Instead, it views the urban condition as a gradient field of influence. Kokkugia's *Swarm Urbanism* project (2009) uses SI as a self-organising generative environment for a redesign of the Melbourne Docklands. A category of agents aggregate matter to form in a stigmeric process, following rules of interaction similar to termite swarms.

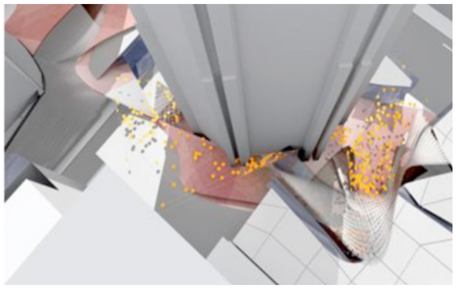 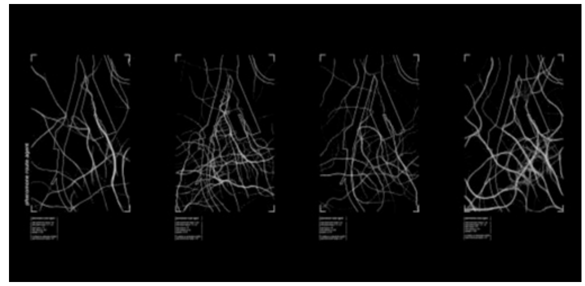

FIGURE 2  a) URL: http://www.kokkugia.com/swarm-urbanism/emergent-field and b) URL: http://www.kokkugia.com/swarm-urbanism

On a more conceptual level, Kas Oosterhuis referred to *swarming* as a novel mode of thinking about architectural design which would replace substantial forms and orderings with an encompassing notion of architecture as information flow.[4] It centered around the structuring of various movement vectors in a distributed system of different interacting agents – that is, people, materials, or environmental forces: »An individual architect will no longer be tempted to have the illusion of complete control over the process. [...]. Now, in the beginning of the twenty-first century architecture is going wild [...].«[5]

Architectural design can benefit from the algorithmic logics of SI and ABM: *First*, such softwares extend the possibilities of handling and optimizing the complex interplay of various input variables for building processes. *Second*, the agent collectives – if appropriately tuned – will self-organize in a number of probably interesting or desirable forms *over time*. In this transformation towards a time-based perspective, architecture becomes based on movements. *Third*, it introduces a novel kind of futurology into architecture. With computer experiments in ABM software, a great number of different scenarios can be tested and evaluated against each other, opening insight in a variety of different desirable futures. And *fourth*, the capacity of adding ever more elements to the 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.

All this indicates a turn from an analytical to a synthetic approach and to a novel cultural technique to dispose of and to arrange the world we live in – with novel potentials for architectural design and construction.[6]

4 Kas Oosterhuis: 'Swarm Architecture,' accessed November 28, 2016, http://www.oosterhuis.nl/quickstart/index.php?id=538.

5 Ibid.

6 This is reflected in a number of further conceptual papers, e.g. Sebastian von Mammen and Christian Jacob, 'Swarm-Driven Idea Models – From Insect Nests to Modern Architecture', *WIT Transactions on Ecology and Environment* 113 (2008), 117-26; Yifeng Zeng, Jorge Codero, et. al., 'SwarmArchitect. A Swarm Framework for Collaborative Construction', in *Proceedings of the 9th Annual Conference on Genetic and Evolutionary Computation* (2007), 186; Pablo Miranda Carranza and Paul Coates, 'Swarm Modelling. The Use of Swarm Intelligence to Generate Architectural Form,' accessed November 28, 2016, http://www.generativeart.com/on/cic/2000/CARRANZA_COATES.HTM; Julian Nembrini et al., 'Mascarillion: Flying Swarm Intelligence for Architectural Research,' accessed November 28, 2016, http://infoscience.epfl.ch/record/50996; see as an overview also Sebastian Vehlken: 'Swarming. A Novel Cultural Technique for Generative Architecture,' *Footprint* 15 (2014) (= Special Issue Data-Driven Design, ed. Henriette Bier, Terry Knight), 9-17.

# 2 Fast, cheap, and out of control

Since serveral years, yet another connection of swarming and architecture becomes apparent. In February 2014, a robotics team of Harvard University presented a robot collective called *TERMES*. 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.«[7] After running the 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: Swarms, in this example, not only participate in the architectural design process in the form of ABM, but actually serve as *builders* of architectural structures. (Fig. 3)

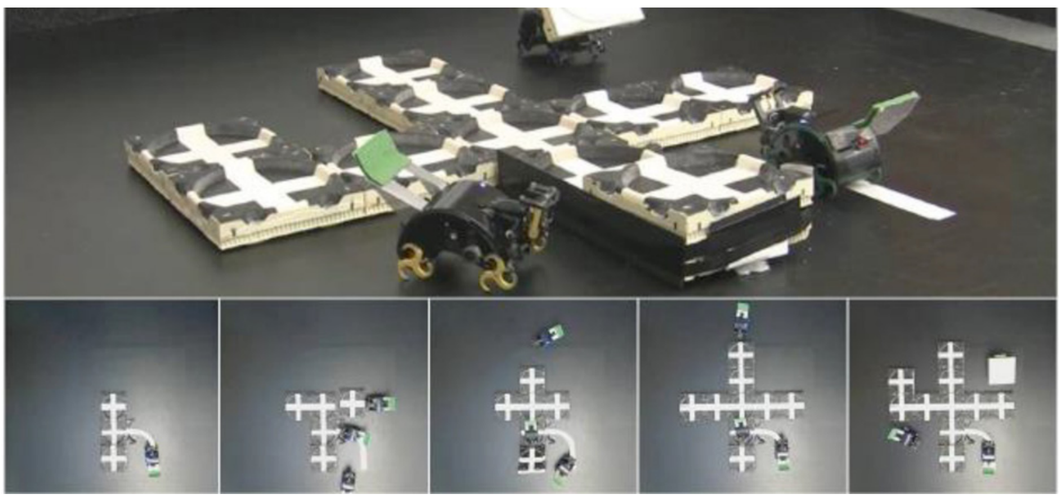

FIGURE 3 Kirstin Petersen, 'Collective Construction by Termite-Inspired Robots,' (PhD thesis, Harvard University, 2014), 72.

*TERMES* can be perceived as a temporary apex of the scientific field of swarm robotics, a research area which is highly connected with the media history of swarm intelligence. A brief historical account on swarm robotics highlights the basic ideas that until today guide projects like *TERMES*, and which, at the same time, also inform the conception of *Robotic Building*.

Three seminal examples are worth mentioning. The first is *Genghis*, one of the first hexapod robots, on first sight resembling a cockroach and not a swarm. (Fig. 4) But this view is misguided. Developed by Rodney Brooks at MIT in 1989, *Genghis* followed an novel Artificial Intelligence paradigm.[8] Instead of the highly abstract, top-down-designed electronic minds of GOFAI, he explored the capabilities of relatively simple robots to adaptively self-organize in a complex environment. The key term was *embeddedness*, and the conceptual principle was bottom-up: A robot based on the autonomous collection and coordination of information from a dynamic environment by a massive parallel coupling of simple elements.

7 Justin Werfel, Kristin Petersen and Radhika Nagpal, 'Designing Collective Behavior in a Termite-Inspired Robot Construction Team', *Science* 343 (2014): 754-758.

8 Rodney A. Brooks and Anita M. Flynn, 'Fast, Cheap, and out of Control: A Robot Invasion of the Solar System,' *Journal of The British Interplanetary Society* Vol. 42 (1989): 478-485.

With its internal network of 57 Finite-State-Machines – most of them for the independent motor control of every leg, the rest for sensing purposes – *Genghis* performed self-organised, robust movements. Without being programmed to ›move forward‹, and based only on the local combination of partial information of the system in its sub-elements, the neighborly coordination of leg positions produced this behavior. It wasn't *Genghis* walking with its legs, but its legs – communicating like a swarm – walked the robot.

The second example is a conceptual paper by Gerardo Beni and Jing Wang on the topic of Cellular Robotics from 1989. At that time, this field was closely related to the theory of cellular automata and to mathematical optimization theory, and thus far from physical implementation. At the heart of their paper – which originated the term *swarm intelligence* – was a principle that the computer scientist Erol Sahin later described as follows: »Swarm robotics is the study of how a large number of relatively simple physically embodied agents can be designed such that a desired collective behavior emerges from the local interactions among agents and between the agents and the environment.«[9] The advantages of such a design compared to more complex single robots consist – theoretically, at least – in its greater robustness, flexibility, and scalability. 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‹.«[10]

And as distributed systems, swarm robotics come with an explicit spatial advantage. 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.[11] The swarm-bots would synchronize with events in space by tracking, anticipating, and level them by self-formation.

A third example derives from a publication that presented an ABM which accomplished a variety of building procedures by combining the biological principle of *stigmergy* – which is known from social insects – with a genetic optimization algorithm.[12] In the model, agents move in a three-dimensional grid and drop elementary building blocks depending on the configuration of blocks in their neighborhood. By evaluating a large number of iterated processes of self-assembly of random space-filling forms by a genetic algorithm, 'interesting' spatial structures emerge, some even looking like wasp nests.[13] As an outcome, the authors were able to find interaction patterns which would lead to collectively built regular structures, without involving a central controller.

9 Erol Sahin, 'Swarm Robotics: From Sources of Inspiration to Domains of Application', in: *Swarm Robotics*, ed. Erol Sahin and William M. Spears (New York: Springer, 2008),10-20.

10 Joshua J. Corner and Gary B. Lamont, 'Parallel Simulation of UAV Swarm Scenarios,' in *Proceedings of the 2004 Winter Simulation Conference*, ed. R. G. Ingalls, M. D. Rossetti, J. S. Smith, B. A. Peters, 355-363.

11 Gerardo Beni: 'From Swarm Intelligence to Swarm Robotics,' in: *Swarm Robotics*, ed. Erol Sahin and William M. Spears (New York: Springer, 2008), 3-9. Gerardo Beni 'Order by Disordered Action in Swarms', in: *Swarm Robotics*, ed. Erol Sahin and William M. Spears (New York: Springer, 2008), 153-172.

12 Eric Bonabeau, Marco Dorigo and Guy Theraulaz, *Swarm Intelligence. From Natural to Artificial Systems* (New York: Oxford University Press, 1999).

13 See ibid.

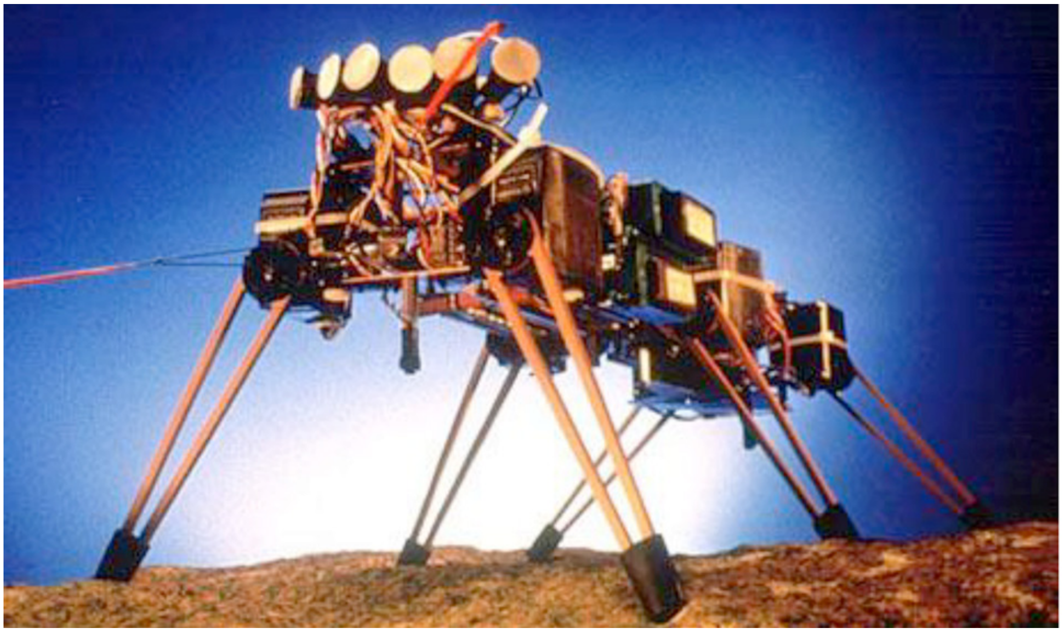

FIGURE 4 URL: http://groups.csail.mit.edu/lbr/genghis/

FIGURE 5 URL: http://motherboard.vice.com/de/read/ein-schwarm-von-1000-robotern-in-perfekter-zusammenarbeit

# 3 Making arrangements

Despite the fact that the epistemological background for the actual implementation of swarm robotics already formed in the late 1980 and 1990s, and although a search on this keywords today retrieves about 1,500 hits on the *IEEE Xplore* platform alone, still very few of these projects and papers actually explore the usablity of swarm robotics for architectural building. Even if robots have been successfully used in construction already in the 1990s, the application of theoretical and computer-experimental work on swarm robotics to physical robots, and the use of autonomous swarms in construction is still work in progress. Swarm robotics develops along three different relations between swarms and space which can only be briefly sketched here and which respective relation to robotic building will need further specification:

First, swarm robotics explores the architecture of swarms, that is, their modes of interaction, synchronization, and emergent collective motion. They test the self-assembly of autonomous elements into a dynamic, but cohesive arrangement – airborne, like in drone collectives such as COLLMOT of ELTE University Budapest, or on the ground, like in the KILOBOT project of Harvard University. In these cases, swarms establish a specific ›swarm space‹, which then can be used, for instance, to more efficiently monitor a physical space than a single robot or drone.[14] (Fig. 5)

Second, swarm robotics achieve tasks of *a manipulation of objects in space* in a self-organized fashion. In a coordinated effort, the collectives push or drag objects around, thus leading to a re-arrangement or sorting of elements of a given space.[15] (Fig. 6)

Third, swarm robotics engages in *actual building tasks* – also with aerial and grounded collectives. For instance, a research group of ETH Zürich experiments with *Aerial Robotic Construction*, based on a quadrocopter collective that arranges standardized lightweight brick elements to non-trivial architectural shapes. (Fig. 7) And the abovementioned *TERMES* collective follows the trail of stigmergy-based building processes, transforming computer simulations like Eric Bonabeau's wasp nests into physical architectural forms.[16]

14 See e.g. Bence Ferdinandy, Kunal Bhattacharya, D. Ábel and Tamás Vicsek, 'Landing together: How flocks arrive at a coherent action in time and space in the presence of perturbations,' *Physica A* 391 (2012), 1207-1215; Michael Rubenstein, Christian Ahler and Radhika Nagpal, 'Kilobot: A Low Cost Scalable Robot System for Collective Behaviors,' *Proceedings of 2012 IEEE International Conference on Robotics and Automation* (2012).

15 Adrian Cabrera de Luis, 'Collective transport in large swarms of simple robots'(MA thesis, Harvard University, 2012), accessed November 28, 2016, https://www.eecs.harvard.edu/ssr/papers/epflmasters12-cabrera.pdf; C. Ronald Kube and Hong Zhang, 'Collective Robotics: From Social Insects to Robots,' *Adaptive Behavior* vol. 2 no. 2 (1993): 189-219; R. Groß, M. Bonani, F. Mondada, M. Dorigo, 'Autonomous Self-assembly in a Swarm-bot', *IEEE Transactions on Robotics* vol. 22(6) (2006): 1115-1130; Vito Trianni and Marco Dorigo: 'Self-Organisation and Communication in Groups of Simulated and Physical Robots,' *Biological Cybernetics* 95(3) (2006): 213-231.

16 See Federico Augugliaro et al., 'Building Tensile Structures with Flying Machines,' (paper presented at IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) November 3-7, 2013); see Jan Willmann et al., 'Aerial Robotic Construction Towards a New Field of Architectural Research,' International Journal of Architectural Computing 3/10 (2012), 439-459.

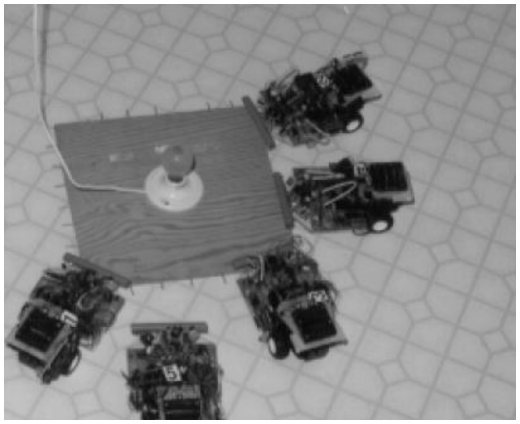

FIGURE 6 C. Ronald Kube and Hong Zhang, 'Collective Robotics: From Social Insects to Robots,' Adaptive Behavior vol. 2 no. 2 (1993), 189-219: 216.

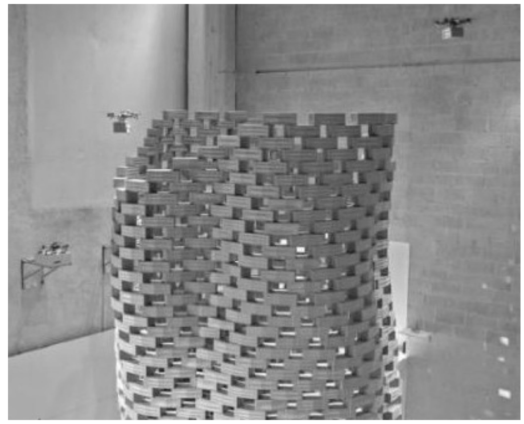

FIGURE 7 Jan Willmann et al., 'Aerial Robotic Construction Towards a New Field of Architectural Research,' International Journal of Architectural Computing 3/10 (2012), 439-459: 454.

In contrast to already existing forms of robotic building, one can stress several advantages: 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. Furthermore, swarm robotics overcome the stationary method of already established 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 eventually, 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.[17]

However, the actual construction of reliable real-size buildings by autonomous swarm robots poses a number of challenges. To date, even the aforementioned *experimental* systems prove to be far too unreliable, error-prone, and ineffective to question existing top-down methods. But nonetheless, it can be correctly stated that the introduction of swarm robotics to architecture »radically extends the traditional spectrum of architectural manufacturing methods«[18], and creates a new level of robotic use in architecture. Swarm Robotics pursues and concretizes the shift in architectural computation brought about by a discourse of swarm intelligence, thereby putting an emphasis on the significance of synchronization and timing of parallel tasks. Or, to reformulate a statement by the *Aerial Robotic Construction* working group, to a far greater extend as other automaticized building methods, swarm robotics is »a vision of process.«[19] A vision which demands further attention and explication.

17 See Kirstin Petersen, 'Collective Construction by Termite-Inspired Robots,' (PhD thesis, Harvard University, 2014), accessed November 28, 2016, https://dash.harvard.edu/bitstream/handle/1/13068244/Petersen_gsas.harvard.inactive_0084L_11836.pdf?sequence=1.

18 Jan Willmann et al., 'Aerial Robotic Construction Towards a New Field of Architectural Research,' *International Journal of Architectural Computing* 3/10 (2012), 439-459: 456.

19 Ibid., 456.

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