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Contents

Introduction

Data-Driven Design to Production and Operation

Henriette Bier and Terry Knight, editors

In the last decades, digital technology has introduced data-driven representational and generative methodologies based on principles such as parametric definition and algorithmic processing. In this context, the fifteenth issue of *Footprint* examines the development of data-driven techniques such as digital drawing, modelling and simulation, with respect to their relationship to design. The data propelling these techniques may consist of qualitative or quantitative values and relations that are algorithmically processed. However, the focus here is not on each technique and its respective representational and generative aspects, but on the interface between these techniques and design conceptualisation.

Data-Driven Design (Conceptualisation)

The dynamics between data-driven processes and design are addressed in this issue in relationship to artistic and architectural production. Such data-driven production may employ real-time values; that is, data collected from the environment, users, and so on, that are involved in artistic or architectural production, as well as assumed values that represent, for example, formal, functional and other requirements. Both real-time and assumed values inform design conceptualisation through to design production, and are encoded in information and knowledge that are employed for representational, generative or other (materialisation and operational) purposes.

In this context, the representation and generation of design conceptualisations interface with data-driven drawing, modelling and simulation at the levels where representational (2D) drawings increasingly become (3D) parametric models on which generative (4D) simulations may be implemented. Parametric systems incorporate characteristics and behaviours representing the design systems themselves, whereas simulations show the operation of the systems in time. Simulations are discussed in this issue partly with respect to their ability to represent and confirm assumptions and improve (optimise) design solutions, but even more so with respect to their generative potential based on emergence. Such generative potential implies that designs emerge from a process in which the dynamics of all parts of the system generate the result, and the architect and artist increasingly become the designers of a process rather than (only) a result.

Generative design processes are increasingly converging towards incorporating aspects of materiality, which DeLanda theorised in relation to the Deleuzian understanding that matter itself has the capacity to generate form through immanent, material, morphogenetic processes.[1] As explored in this issue, these processes often include the systemic interaction between human and non-human components. Creativity and authorship thus become hybrid, collective and diffuse, whereas agency, as pointed out by Latour, is increasingly located in neither human nor non-human system components, but in the heterogeneous associations between them.[2]

Data-driven generative systems are wide-ranging in approach and results, and include, for example, cellular automata, grammars, and multi-agent systems. This issue focuses in particular on the generative potential of multi-agent systems based on self-organisation. Self-organisation is a process in which the organisation of a system emerges bottom-up from the interaction of its components.[3] Multi-agent systems – for example, *swarms* – are employed in generative design processes that deal with large quantities of data, which sometimes feature conflicting attributes and characteristics.[4] These attributes and characteristics are incorporated in behaviours based on simple rules whereby agents interacting locally with one another and their environment instigate the emergence of complex, global behaviour. The use of artificial or non-human agents in design is of relevance because of their ability to embody both natural (human) and artificial (design-related) aspects. Natural aspects may reflect human needs, for example, bodily comfort, whereas artificial aspects may indicate, for instance, spatial relations or structural and materialisation requirements.

Multi-agent systems are set up basically as parametric models incorporating characteristics and behaviours representing the natural and artificial aspects of the systems, whereas simulations of behaviours show the operations of such systems in time.[5] The parametric model may consist of all data (incorporating real-time and assumed values) pertaining to an architectural design, while simulations in time may produce ranges of design results, from sub-optimal to optimal (spatial) results. An optimal result indicates a best (or most favourable) condition from a set of comparable circumstances. The assumption is that simulations establish a feedback loop between, for example, architectural production and the operation of the architectural system in time.

Simulations employing multi-agent systems consist of artificial agents that are conceived similarly to natural or human agents as autonomous entities able to perceive through sensors and act upon an environment through actuators.[6] Interactions between human and artificial agents may follow principles as described in Actor–Network Theory (ANT), implying that material-semiotic networks are acting as a whole; in other words, the clusters of actors or agents involved in creating meaning are both material and semiotic.[7] ANT, therefore, implies the agency of both humans and non-humans – agency is not located in one or the other but in the heterogeneous associations between them. Authorship is collective, hybrid and diffuse.

Multiple, alternative designs may emerge from the interaction between natural and artificial agents in such heterogeneous generative processes. Furthermore, the same data collection may be encoded and algorithmically processed or simulated in different ways. For instance, artistic and architectural production resulting from swarming processes demonstrates that under similar conditions, same or similar (virtual and physical) agent systems may produce multiple (or endless) variations of artworks and architectural artefacts due to the emergent properties of the system.

From Data-Driven Design to Materialisation and Use

Data-driven design processes are investigated in this issue in relation to the production of artistic and architectural representations, simulations and materialisations. Virtual representations may be parametric models and simulations, while physical materialisations may be drawings, models and buildings. While representations and simulations exploit the ability of data to incorporate information and knowledge with respect to geometry and pre-materialisation behaviour, they also increasingly incorporate aspects of materialisation and even post-materialisation behaviour.

Thus data-driven design processes increasingly include, or are linked to, materialisation, fabrication or construction processes. Not only can data-driven art and architecture be designed and fabricated by digital means, but they can also incorporate information, knowledge, and sensing-actuating mechanisms that enable artefacts from paintings to buildings to have real-time operation and interaction with environments and users.[8] Indeed, in the last decade an important issue for data-driven design has been how to better serve everyday life by embedding information and knowledge into environments through real-time interactions between natural or artificial environments and users. The assumption is that data-driven design should establish a feedback loop from conceptualisation to materialisation and use. And, as already envisioned in the 1970s by Eastman, such feedback systems today are progressively allowing architecture to self-adjust in order to fit the needs of users.[9]

Data is thus increasingly able to encode information, not only about design and about materialisation but also about the operation and use of buildings or other artefacts and their components. Data becomes a single source for conceptualisation, production and operation.

Authors' Contributions

The dynamics between data-driven processes and design, as well as the impact of these processes on artistic and architectural production, have been addressed in five papers from authors with diverse backgrounds in media studies, art and architecture. From theoretical explorations that discuss cultural swarming techniques and data-driven design representation and materialisation aspects, to practical (artistic and architectural) experimentation, this issue indicates the increasing convergence of computational and material systems. Furthermore, it addresses the generation of multiple results from one and the same computational representation, with a specific focus on generative aspects based on swarms. These multiple results may be realised virtually and, more and more often, they are also realised physically.

The issue begins with Sebastian Vehlken's essay on data-driven, self-organising systems, in particular, Agent Based Modelling (ABM) and its offshoot, Swarm Intelligence (SI). In 'Computational Swarming: A Cultural Technique for Generative Architecture', Vehlken frames ABM and SI as fundamental cultural techniques for understanding and shaping dynamic processes across diverse domains, and maps out their unique potentials for architectural and urban design. He sets the time-based, emergent qualities of ABM and SI against earlier computational techniques such as parametric and geometric modelling, in which the scope of problem solutions are static and known in advance. Swarm systems are proposed as especially well suited for addressing opaque or ill-defined architectural or urban design problems, and for modelling interactions of heterogeneous elements within complex design scenarios. He further suggests that swarm and agent-based systems are natural bases for innovating novel material and physical fabrication methods, for predicting building performance and use within varying environmental contexts and, still further, for facilitating collective work practices and the inclusion of clients and stakeholders in dynamic and real-time processes.

Within this expansive discussion, Vehlken raises the critical question of the role of the designer. Who or what controls these systems? Where are the hand and the intelligence of the designer in these seemingly self-driven systems? Vehlken cites the architectural design work and views of Roland Snooks on agent-based methods in order to foreground the need to open the black box and intervene in the autonomy of these systems. The architect should be responsible for defining system rules in relation to specific design problems, for thoughtfully guiding trial-and-error runs of the system, and for evaluating and selecting from possibly myriad results.

Aspects of Vehlken's commentary are illustrated nicely in an early implementation of swarm intelligence in art making. In 'A New Kind of Art', Leonel Moura and Henrique Garcia Pereira describe their pioneering experiment in generating art through swarm-animated robots. Their *Artsbot* project, an outgrowth of work in robotics, artificial life and, in particular, insect swarming behaviour, consists of painting and drawing robots steered by sensors and actuators. The robots interact on a local level with an environment (a canvas) and with one another to generate complex, emergent, global behaviours that result in abstract paintings. Moura and Pereira's objectives here for data-driven, artistic production stand in striking contrast to Snooks's objectives for architectural production. The autonomous behaviour of the painting robots is essential to *Artsbot*. The goal is to take the human out of the loop at the production (but not at the conceptualisation) level, and to maximise the autonomy and creativity of machines (robots) and the system driving them.

Issues of complexity and data-driven, generative processes are taken up by Zeynep Mennan in 'Minding the Gap: Reconciling Formalism and Intuitionism in Computational Design Research'. Mennan observes a trend in computational research to take on design problems of increasing complexity. This trend is fuelled by, and in turn has fuelled, a rise in formal, computational techniques that make use of numerical, quantitative data that expedite the processing of complexity. Mennan presents this ever-expanding project of formalisation and 'naturalisation', which privileges the objective and scientific, as a profound shift from phenomenological approaches that emphasise subjective experience and intuition, and are deployed through non-quantitative, spatial, and graphic (drawing) practices.

The question, then, for Mennan is how to reconcile formalist and phenomenological traditions: how to give meaning, content, and interpretation to intangible data, and how to compensate for the alienation and estrangement provoked by abstract, numerical representations. She observes that the problematics of purely formalist approaches are increasingly addressed in contemporary efforts to integrate computation with some level of reality through physical/material production. Furthermore, she finds promising paths toward reconciliation in the ways in which some contemporary architects are engaging generative design strategies. Like Sebastian Velken above, Mennan references Roland Snooks, as well as his contemporary Tom Wiscombe, who decry the loss of content in purely data-driven systems, and who experiment with strategies for embedding the designer's intuitive and subjective decision-making processes into iterative feedback loops within generative models.

What for Mennan is a shift from the phenomenological to the computational is for Eran Neuman a shift from the metaphorical to the literal. In 'Data Reshaped: Literalism in the Age of Digital Design and Architectural Fabrication', Neuman sees another side to data, one viewed from the perspective of contemporary production and fabrication processes. Like Mennan, Neuman notes the transition from pre-digital design practices using spatial and graphic media, to contemporary digital practices using formal, abstract data. But in an interesting counterpoint to Mennan, and from a different vantage point, Neuman points to the incompleteness of pre-digital representations – they are metaphorical and analogical and thus need be augmented to be realised in different media and contexts, for example, in materialisation and building. And instead of viewing what is lost in the transition to digital representations, Neuman identifies what is filled in. Digital data is replete with information sufficient for multiple, parallel realisations – as a design model, as a physical prototype, and so on. These different data manifestations are *literal* with respect to one another. Importantly, the literalism of digital data and its ability to be articulated in diverse media relies on its lack of external signification, symbolism, or meaning.

Neuman characterises the contemporary phenomenon of literalism in architectural design and production as *digital literalism*. He traces the development of this phenomenon in relation to earlier theories of literalism in literature, art, and other fields, and identifies the locus of new, digital literalism in process rather than object. In so doing, he adeptly relates digital literalism to contemporary digital design discourse concerning the shifting emphasis from space to time, from objects to events, and from material things to process and performance.

Issues of performance, process, time and more are taken up in the concluding paper of this issue, 'Intersecting Knowledge Fields and Integrating Data-Driven Computational Design en Route to Performance-Oriented and Intensely Local Architectures' by Michael Hensel and Søren Sørensen. At the heart of Hensel and Sørensen's discussion is their desire to mitigate the increasing globalisation and homogenisation of architecture. Their counter to this trend is a performance-oriented approach to architecture, an approach that considers the diverse domains of agency – spatial to material to human – within the highly specific or 'intensely local' context of a design problem. Architecture, they contend, should be *non-discrete* from its local environment. It should be attentive to the immediate ecosystem and its modulations over time, harness local resources and processes, and be mindful of culturally specific practices.

The pressing question, then, for Hensel and Sørensen is how to integrate generative and analytical design strategies within a methodological framework that can custom configure to a highly varied range of intensely local scenarios. They propose several lines of inquiry that respond to this question, and describe how these have been tested in design experiments and research projects. Tools deployed include the use of 'live' or real-time, time dependent environmental data, locally appropriate materialisation and fabrication techniques, and augmented or virtual reality visualisation methods for understanding the complex performative conditions of architecture. Importantly, locally specific real-time data sets may not only serve design conceptualisation but may also facilitate post-occupation analysis. This analysis is necessary for real-time operation of buildings in order to serve everyday needs. In sum, Hensel and Sørensen seek to integrate and exploit the capacities of data-driven design methods in their advancement of an intensely local performative architecture.

Conclusion

Data-driven design is investigated in this issue in relation to artistic and architectural production in which representations and simulations exploit the ability of data to incorporate information and knowledge with respect to geometry, materialisation, and pre- or even post-materialisation behaviour. Thus data increasingly encodes information not only about materialisation but also the operation of building components. Design becomes process- instead of object-oriented, and use of space becomes time- instead of programme- or function-based. Architects increasingly design processes in which users operate multiple time-based architectural configurations emerging from the same physical space. The space may reconfigure physically or sensorially in accordance with environmental and user specific needs.

Similar to process-based artistic and cultural production, data-driven architecture exploits emergent results from interactions between human and non-human agents. However, data-driven architecture aims to exploit emergent phenomena not only at the design and production level but also at the building operation level, wherein users contribute to the emergence of multiple architectural configurations. In this context, agents, whether human or non-human, virtual or physical, enable information and knowledge to be embedded into processes and environments that aim to serve everyday life.

The question of how information and knowledge may be embedded into processes and environments in order to serve everyday life has been tentatively answered in the last decade by introducing spatial reconfiguration, which is facilitating multiple, changing uses within reduced timeframes.[10] Furthermore, interactive energy and climate control systems that are embedded in building components and employ renewable energy sources, such as solar and wind power, aim to reduce architecture's ecological footprint while enabling a time-based, demand-driven use of space.

Thus, the development of data-driven techniques, such as digital drawing, modelling and simulation, inform design today at parametric, geometrical, material and behavioural levels, where behaviour implies not only virtual behaviours enabling simulations, but also physical behaviours of architectural systems operating in real-time. Therefore, the representation and generation of design conceptualisations interface with data-driven drawing, modelling and simulation at the levels where 2D drawings become 3D parametric models on which 4D simulations are implemented. These, in turn, interface with the real-time operation of physically built architectural systems. Data-driven design thereby establishes an unprecedented design to production and operation feedback loop.

Notes

1. Manuel DeLanda, 'Deleuze and the Use of the Genetic Algorithm in Architecture', in *Architectural Design - Contemporary Techniques in Architecture*, ed. by A. Rahim (London: John Wiley & Sons, 2002), pp. 9-12. See also Manuel DeLanda, *Philosophy and Simulation: The Emergence of Synthetic Reason* (London: Continuum, 2011).
2. Bruno Latour, *Reassembling the Social: An Introduction to Actor-Network-Theory* (Oxford: OUP, 2005).
3. Henriette Bier et al., 'Building Relations' in *Architectural Annual 2005-06*, ed. by H. Bekkering (Rotterdam: 010-Publishers, 2006), pp. 64-7. See also Stuart Russell and Peter Norvig, *Artificial Intelligence - A Modern Approach* (Upper Saddle River: Prentice Hall, 2003).
4. Henriette Bier et al., 'Building Relations'.
5. Manuel DeLanda, 'Deleuze and the Use of the Genetic Algorithm in Architecture'
6. Henriette Bier et al., 'Building Relations'. See also Stuart Russell and Peter Norvig, *Artificial Intelligence - A Modern Approach.*
7. Bruno Latour, *Reassembling the Social: An Introduction to Actor-Network-Theory*
8. Henriette Bier and Terry Knight, 'Digitally-Driven Architecture', in *Footprint Issue 6*, ed. by H. Bier and T. Knight (Amsterdam: Technepress, 2010), pp. 1-4.
9. Charles Eastman, 'Adaptive-Conditional Architecture', in *Design Participation: Proceedings of the Design Research Society's Conference Manchester, September 1971*, ed. by Nigel Cross (London: Academy Editions, 1972), pp. 51–7.
10. Henriette Bier and Terry Knight, 'Digitally-Driven Architecture'.

Biographies

Henriette Bier graduated in architecture (1998) from the University of Karlsruhe in Germany, and afterwards worked with Morphosis (1999-2001) and ONL (2003) on internationally relevant projects in the US and Europe. She taught computer-based architectural design (2002-2003) at universities in Austria, Germany, Belgium and the Netherlands, and since 2004 she has been mainly teaching and researching at the Delft University of Technology with a focus on digitally driven architecture. She initiated and coordinated the workshop and lecture series on Digital Design and Fabrication (2005-06) with invited guests from MIT and ETHZ, and in 2008 finalised her PhD on System-Embedded Intelligence in Architecture. Results of her research have been published internationally in books, journals and conference proceedings, and she regularly lectures and leads workshops worldwide.

Terry Knight is a Professor of Design and Computation in the Department of Architecture at the Massachusetts Institute of Technology. Her research and teaching centre on the theory and application of shape grammars. Her book, *Transformations in Design,* is a well-known introduction to the field of shape grammars, and she has published extensively on shape grammars and related topics in international design research journals. Her recent work is in the new area of Computational Making, where she is exploring the incorporation of sensory, experiential and improvisational aspects of making things into computational systems. She has served on the editorial boards of *Languages of Design*, *Environment and Planning B: Planning and Design*, *Journal of Mathematics and the Arts*, *ArchiDoct* and *Design Science Journal*. She holds a BFA from the Nova Scotia College of Art and Design and a MA and PhD in Architecture from the University of California, Los Angeles.

Computational Swarming: A Cultural Technique for Generative Architecture

Sebastian Vehlken

> We can think about form simply as organization.
> (Roland Snooks)[1]

Shaken or Stirred: Do I Look Like I Give a Damn?

Mies van der Rohe, a notoriously heavy drinker who allegedly asserted that architecture is no cocktail, most certainly would have been surprised by the theoretical and aesthetical mixtures that came along with the advent of digital technologies in architectural design and construction.[2] From the early 1990s onwards, novel approaches such as *digital tectonics* paralleled the invention of *spline modeller* software tools. Architects started manipulating continuous curved lines directly on computer screens. They mass-produced blob-like forms and challenged former modernist concepts of ordering space by introducing notions of foldings (Greg Lynn) or field conditions (Stan Allen) that adhered to the effects of dynamic environmental conditions on the process of shaping.[3] Accompanied by poststructuralist philosophical thought, such as Gilles Deleuze's conceptions of the fold, morphogenesis, involution/evolution and the objectile, or Bernard Cache's and Manuel DeLanda's advancements in topological architecture – or even a 'biology of cities' – the digital turn in architecture fostered a fascination for time-based, multiple, highly interconnected and evolutionary processes.[4] The crucial design choice became how to set adequate limits for variations, changing the role of the architect from designing a static result to arranging various dynamic processes with multiple instantiations of possible outcomes. An effect of this was that parametricism allegedly became the ultimate 'new global style for architecture and urban design'.[5] However, this early and influential cocktail of poststructuralist philosophy and digital architecture often diluted the specific 'materialities' of computer technology, design software, or animation tools which only enabled the handling of such complex agglomerates of data. It expressed, rather metaphorically, a conceptual shift towards the generative aspects of non-linear feedback processes, towards emergent characteristics and towards self-organising systems.

This became even more obvious when architects such as Kas Oosterhuis took these approaches further during the last decade. He not only emphasised the ongoing gamification of architectural design, but also, in a rather counterintuitive way, referred to *swarming* as a novel mode of conceptualising architectural design.[6] Swarm Architecture, Oosterhuis claimed, would replace substantial forms and orderings with an encompassing notion of architecture as information flow. It centred on the structuring of various movement vectors within a distributed system of different interacting agents (people, materials, environmental forces, etc.). Moreover, with its appeal to the bottom-up principles and emergent global behaviour of Agent-based Modelling and Simulation (ABM), it also transcended the generative principles of spline modelling and parametric design. As Australian architect Roland Snooks adds:

> I consider parametric and emergent as polar opposites. Within parametric hierarchical tools all possibility is given within the starting condition, while emergent conditions arise from non-linear systems such as multi-agent models. […] What we are interested in is looking at design from the smallest element and the way that generates order at the macro level.[7]

Or, as Oosterhuis put it in his paper on swarm architecture: '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 […].'[8] Such architectural concepts were embedded in a recent boom of swarming phenomena in many cultural and socio-historical debates. From this continuing discourse stems, once again, a certain reflex in architectural thought to mix together (philosophical) concepts of emergence,[9] rhizomatic networks,[10] socio-political multitudes,[11] and social swarming phenomena in humans.[12] If, for instance, architect Neil Leach in a recent article sketches out the potentials of *Swarm Urbanism*, this might well provide an instructive reading, but it nevertheless neglects important differentiations between these concepts.[13]

Hence, in seeking to avoid a repetitive application of imprecise philosophical cocktails informed by a metaphorical understanding of swarming and the related notions of collective dynamics, this article proposes to examine swarm architecture and urbanism from another angle. It follows a media-technological perspective that complements a broader *Philosophy of Simulation* and its significance for contemporary architectural theory.[14] The hypothesis of this paper is that Swarm Intelligence (SI) and ABM have become fundamental cultural techniques for understanding and governing dynamic processes. These techniques hold tremendous potential for (generative) architectural design. Today's widespread distribution of SI and ABM software tools is therefore based on a reciprocal computerisation of biology and the biologisation of computer science, which have to be understood less in a philosophical sense than in a media-historical perspective.[15] Thus, the second part of this paper, *Neighbourhood Technologies*, briefly introduces the concepts of SI and ABM and sketches out their aptitude for generative and data-driven architectural approaches. In the third part, these media technologies will be situated in a broader contemporary cultural theory called *Cultural Techniques*. This enables the description of novel architectural concepts like swarm architecture to find their place in a theoretical alliance between technologies and cultural practices, thus challenging and complementing the mere conventional philosophical connotations of architectural theory. The fourth part, *From Insect Media to Bodies with a Vector*, examines more closely possible media-technical groundings and genealogies of multi-agent approaches in generative architecture. Finally, the fifth and last part, *Superconnected Idiot Savants*, critically evaluates some political implications that adhere to the seemingly democratising structure of these distributed design systems.

Neighbourhood Technologies

Computational Swarm Intelligence, according to a common notion, is a kind of science from the bottom-up. Or, to put it another way, '[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".'[16] It is grounded in the idea that the complex adaptive behaviour of a system at the global level can be effected by multiple, parallel interactions of very simply constructed individuals at the local level, when they follow a set of only a few behavioural rules like avoidance (avoid collision with local flock mates), alignment (steer towards the average heading of local flock mates), and cohesion (steer towards the locally perceived centre of the flock).[17] 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 organise themselves quickly, adaptively and uniquely with the help of their distributed control logic. Within swarms, the quantity of local data transmission is converted into new collective qualities.

Although it has often been stated that SI has been inspired by biological phenomena such as bird flocks, ant and termite swarms, beehives or fish schools, it is important to understand that these phenomena first emerged as operational collective structures by means of a *reciprocal* computerisation of biology, and a biologisation of computer science. In the case of swarms, it is not simply animals that serve as a socio-biological model for mankind and its *technē*. What is noteworthy is rather the reciprocal interference of biological principles and the processes of information technology. Swarms should be understood as *zootechnologies*.[18] In contrast to biotechnologies or biomedia, they derive less from *bios*, the concept of 'animated' life, than they do from *zoē*, the unanimated life of the swarm.[19] *Zoē* manifests itself as a particular type of 'vivacity', for instance, the dynamic flurry of swarming individuals. It is a vivacity that lends itself to technological implementation because it can be rendered just as well into orderly or disorderly movement. This capacity, in turn, is based on rules of motion and interaction that, once programmed and processed by computer technology, can produce seemingly lifelike behaviour among artificial agents. Swarm research combines this *zoē* with the experimental epistemology of computer simulation. In a recursive loop, swarms inspired agent-based modelling and simulation, which in turn provided biological researchers with enduring knowledge about dynamic collectives. This conglomerate led to the development of advanced, software-based 'autonomous particle systems' and turned it into one of the most fruitful sources for the development of distributed models in the ABM software paradigm. One can designate this a *media-emergence* whose decisive impact oftentimes came neither from biology nor from computer science, but rather, for instance, from graphics and animation design.[20]

As an effect, SI and ABM help to configure environments that are increasingly confronted with the task of organising highly engineered and interconnected systems, as well as that of modelling complex correlations. They can be applied wherever there are 'disturbed conditions', wherever imprecisely defined problems present themselves, wherever system parameters are constantly in flux, and wherever solution strategies become blindingly complex. Swarm intelligence, according to one standard work, 'offers an alternative way of designing "intelligent" systems, in which autonomy, emergence, and distributed functioning replace control, preprogramming, and centralization'.[21] With this access, they deeply permeate a vast number of different scientific and cultural fields. SI and ABM appear in economic simulations and models of financial markets, in simulations of social behaviour, in simulations of crowd evacuations, and in the field of panic studies. They have become essential to epidemiology, to the optimisation of logical systems and to transportation planning. They are used to improve telecommunications and network protocols and to improve image and pattern recognition. They are a component of certain climate models and multi-robot systems; they play a role in the field of mathematical optimisation, and, not least, in generative architecture and design.

Architectural design can benefit from the algorithmic logics of SI and ABM in the following ways. First, software of this nature 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 now 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 architecture. 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, a zootechnological and post-humanist element enters the design process. It coalesces more traditional (human) cultural practices of architectural design with novel media technologies. And 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.

If we consider the deep permeation of the above-mentioned vast number of application fields, we can understand zootechnological swarming as a more general technique of operationalising formerly unknowable and indistinct problem spaces. Furthermore, if we acknowledge the shift from an analytical to a synthetical approach as the central element of computational SI and ABM, then this might indicate the emergence of a novel cultural technique to dispose of and arrange the world we live in.

The next part of the article will depict the significance of the concept of Cultural Techniques for architectural theory, and elucidate more precisely the meaning of computational swarming as a novel cultural technique.

Cultural Techniques

The term *Cultural techniques* (German: *Kulturtechniken*) originates from an agricultural discourse from about 1900 that has been revived for cultural analysis by a number of German cultural theorists in order to put emphasis on the dimension of *techné* inherent in cultural practices.[22] Instead of perceiving cultural practices as connected merely to human actors, or processes of culturalisation as an anthropomorphic treatment of objects and things, *techné* makes use of a different understanding of culture. *Cultures* in this sense (in contrast to the notion of a singular, typically 'high' culture) are characterised by a humanoid-technical hybridity. They are conceived of as actor-networks that comprise humans, technical objects, and the respective chains of operations between them. In these operation chains, not only do humans *make use* of technical things or design them according to habitualised body techniques, but also technical objects situate humans in their environment and take an active agency in shaping their self-conception. Cultural techniques seek to describe and analyse 'how signs, instruments, and human practices consolidate into durable symbolic systems'.[23] Or, as media historian Bernhard Geoghegan notes, 'Put in terms familiar to German media theory of the 1980s and 1990s, cultural techniques concern the rules of selection, storage and transmission that characterise a given system of mediation, including the formal structures that compose and constrict this process.'[24]

But why should architectural theory care about such a concept taken from cultural analysis? This becomes clear very quickly if one takes a definition from sociologist Dirk Baecker: in an interpretation that follows Niklas Luhmann's system theory, he assigns to architecture the principal distinction of distinguishing between an *inside* and an *outside*.[25] If this is considered the basic (cultural) operation of architecture, then different media and cultural practices that process this distinction can be examined – a distinction which automatically also relates to material and technical aspects. Thus, a simple fence could be perceived as an architectural invention that discriminates between inside and outside, but it could also be seen as an initial technique that transformed early nomadic cultures into settler cultures. As Bernhard Siegert proposed in a recent article, even a mere door can give rise to a whole system of cultural operations and symbolic, epistemic, and social processes. A door, writes Siegert, not only connects two rooms, it also principally defines a relation between an inside and an outside. According to Georg Simmel, a closed door not only separates two rooms but also functions at the same time as *a sign* of that separation. As a consequence, it both discriminates between physical spaces and designates, for instance, arcane or private spheres. And finally, a door can be operated in various ways that induce different cultural practices: either in an anthropomorphic sense; for instance, by the use of a doorknob and corresponding practices of, say, quietly closing office doors, or in a machinic sense, as in the case of automated doors. Hence, doors can be seen as a (material) architectural medium that becomes a medium for cultural codes and modes of operation.[26] A first argument for an awareness of cultural techniques in architectural theory, then, is their capacity to connect these material, social, symbolic and practical aspects of architecture.

A second argument pertains to the relation of time and space. In another instructive article, Siegert analyses grids as a fundamental cultural technique with close links to architecture. As he points out, grid patterns serve as a technique that helps to structure and control space, as, for instance, in the development of a central perspective, cartography, or architectural construction. But they also help in inventing and generating a future space: for example, by providing an exact layout for the accretion of Roman military camps, or, later, for developing reliable address systems in colonial city planning. These systems are also able to document still empty spaces, and thus enable a rigidly controlled, possible future extension of cityscapes. Grid patterns, as another material form of distinguishing inside/outside relations, thus operate as cultural techniques that can be used both to *represent* and to *generate* (architectural) realities.[27]

To return to architecture's main distinction between inside and outside spaces, the data-driven generative techniques of SI and ABM can be perceived as a novel and synthetic way of mediating between these. SI and ABM build upon a potentially unrestricted number of movement processes that only define the emergence of boundaries between inside and outside during the simulation runs. Their synthetic character is founded on an underlying algorithmic structure that defines neighbourhoods among all kinds of objects. In this case, space as such no longer has to be organised or constituted by a defined geometric grid, but self-generates out of the multiple local interactions of point clouds or particle swarms. Single individuals, architectural bodies of all sizes, their interiors and exteriors and the urban landscapes they populate, can be tentatively modelled on the same algorithmic principle of autonomous neighbourhood interaction along simple rules. And the emerging 'wild' architectures (Oosterhuis) can be made perceivable and manipulable with the help of advanced Computer Graphic Imagery (CGI). As an effect, SI and ABM generate a number of possible future states of buildings, traffic flows or urban spaces under changing environmental influences. Likewise, they enable a comparison between these possible futures.

SI and ABM are novel cultural techniques because they approach complex organisation problems by means of artificial *populations* of agents, and the behaviour of these in time. The movement paths and vectors of populations – not geometric principles – account for this novel architectural approach. Swarming introduces animals into the discourse on Cultural Techniques (and thereby into the discourse on architectural design) – in this case as a multitude or collective – and thus addresses a zootechnological relation. Produced between the fields of biology and computer science, a system's knowledge of self-organising collectives assists us, in a way that anthropology cannot, in our treatment of certain problems and regulatory issues that are normally regarded as opaque. In response to the abovementioned question concerning the operative interconnections between body techniques and media techniques, swarms contribute the element of dynamic collective bodies. Thus, they co-author processes within our knowledge culture that previously were unable to be addressed without their media-technological means. But how, and to what ends, is such software concretely applied in contemporary architectural design?

From Insect Media to Bodies with a Vector

If we consider SI and ABM systems to be novel cultural techniques that help to treat complex architectural problems, we have to distinguish between two strains of self-organisation principles: one looks at the dynamic generation of (architectural) forms in social insects, the other is occupied with the dynamic movement and adaptive capacities of flocks or swarms on the move (such as birds or fish). In terms of architectural design, they serve several functions: first, they can be used to produce idea models; that is, they can inspire new shapes for further design measures as an outcome of emergent processes. Such idea models would not take shape without the algorithmic logic of SI and ABM. 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. And third, novel fabrication techniques that translate virtual models into material fabric can be attached to these computational tools.

The social insects principle relies on a communication structure that uses *stigmergy*, or the more general *sematectonic communication*.[28] This means that the locally defined agents orient themselves not only according to the behaviour of a number of neighbours but also according to traces that the agents place in, and read from, their environment. For instance, pheromone trails to a food source produce a positive feedback for individuals following, and nest structures such as honeycombs determine and incite the building of subsequent structures. This distributed organisation has been formalised in computer simulation models like *Ant Colony Optimisation* (ACO) and initially gave rise to the field of SI.[29] In this ABM paradigm, agents collectively transform the incoming information into behavioural patterns, and at the same time into concrete building structures. '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,' points out media historian Jussi Parikka.[30]

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 equivalent to that found in wasps in nature.[31] 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, for example, *Swarm-Driven Idea Models*. Here, the simulation environment works as a virtual test bed for the 'breeding' of complex emergent architectural constructions.[32] In order to produce constructions that are in some way a suitable response to a given architectural problem, the simulators integrate an evolutionary algorithm into the CS, which rates the

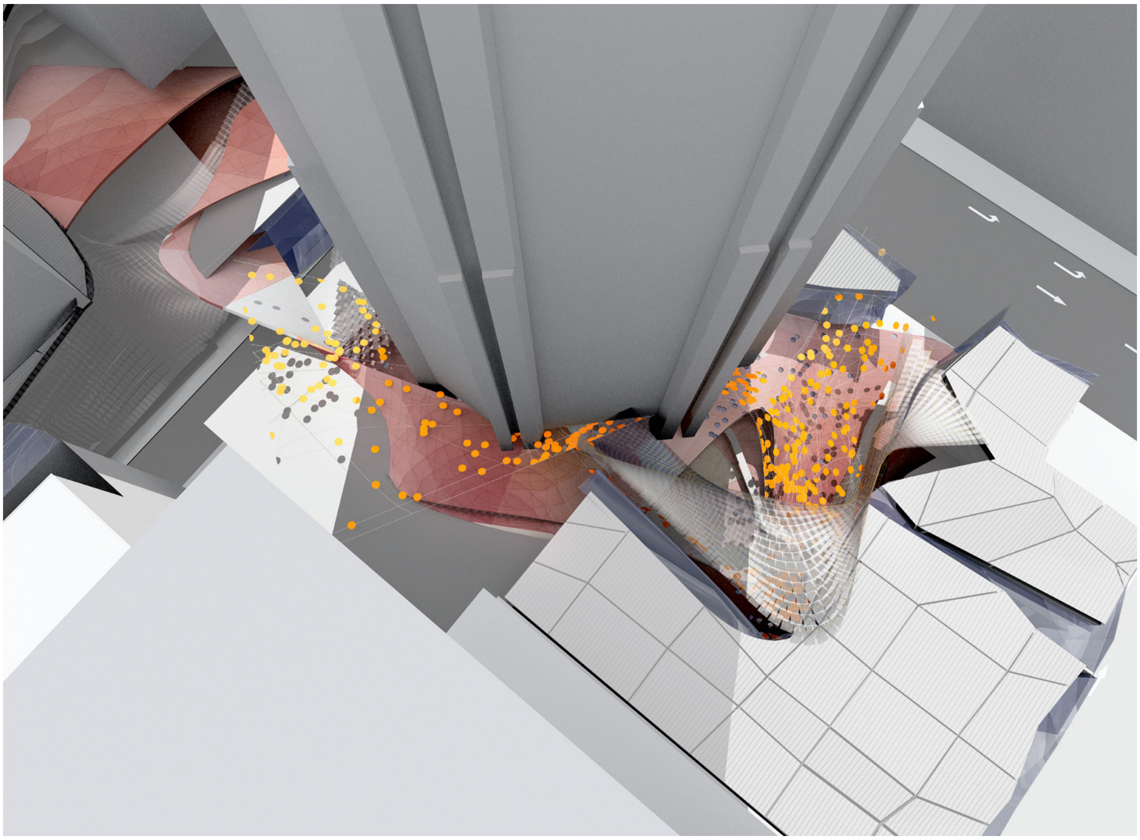

Fig. 1: Kokkugia's *Emergent Field* Project (2003). Modelling of the plaza surrounding Nauru House in Melbourne's CBD as a gradient field of environmental influences. © Roland Snooks

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 predefined evaluation criteria.[33] Thus, SI enables an integration of architecture into the site-specific environmental context, and takes into account aspects of the building's ecological and economic performance.[34] Although one should be rather cautious regarding tendencies to overemphasise the 'natural integrity' of such outcomes of biologically inspired CS, in terms of a generative approach to the creation of architectural idea models, *Insect Media* of this kind 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 'optimisation' of the generation of forms, and, not least, the expertise of the meta-modeller: the architect.

The second principle in SI is based on the above-mentioned 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 formerly unknowable global forms through the non-linear interactions of many mobile individuals. Fuelled by sophisticated CGI techniques, ABM software was soon embraced by a number of architectural design teams. They transformed creation into merely developing adequate rules to govern the assembly of components, thus leaving the architect in the role of meta-designer of self-organising systems.[35] On the one hand, control is thereby handed to the bottom-up self-organisation of non-linear agent systems, while on the other, it is reintroduced 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.'[36]

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.[37]

But this raises the question of how exactly to define the architectural problem. [fig. 1] Due to the non-linear relationality of all objects in a public space, the meta-designers seek to describe in simple rules all sorts of relations pertaining to those objects.[38] In this way, the micro-relations of individual agent behaviour connect with a mesoscale that gives form to single buildings, and to a macroscale of generative urban planning. With ABM software, as Oosterhuis states, such a system will display real-time behaviour, and the parameters may change continuously over time. The crucial point is that comprehensiveness only emerges by running the processes. Therefore, using the tentative technologies of SI and ABM in generative architecture always seems to be a question of how to shape the bottom-up system behaviours 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.[39]

Moreover, instead of working with black box modules of commercial architecture software like *Maya* or *Rhino*, people like Snooks advocate the development of open source programmes specific to the respective design intention: '[T]he algorithm should emerge from the architectural problem rather than simply the architecture emerging from the algorithm.'[40]

To broaden this understanding, the collaborators of the *Kokkugia* project describe swarm-based urban planning as a simultaneous process of self-organising agents which would no longer result in a single, optimum solution or master-plan, but in a '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'.[41] [figs. 2-3] In addition, for *Kokkugia,* the objective of understanding urban dynamics by means of swarm intelligence systems coalesces with generative measures of their non-linear methodologies to produce shapes for 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.[42] [fig. 4] An effect of SI and ABM models, with their focus on moving patterns and dynamic flows, is that the relationship between locally acting autonomous agents and the material composition of architectural buildings and sites can take on novel operational forms. As Neil Leach states, these computer simulation systems integrate the effects of spatial practices (the agents' movements) into the material urban fabric, and, likewise, the constraints imposed on those practices by its (computer-simulated) physicality.

At this point, the effects of SI and ABM as cultural techniques become apparent:

> 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.[43]

SI and ABM can be defined as cultural techniques that facilitate the apprehension of future states of buildings or urban space under varying environmental impacts, which have the potential to deeply change and enhance the procedures of urban planning. However, it has to be kept in mind that such forms of scenario building also become a part of the reality they try to model. And in contrast to weather simulations, for instance, the modelled systems (for example, people using an urban plaza in Melbourne) would certainly react to the scenarios produced by urban planning tools of this kind if these were on display, say, at a community meeting. Such an interaction between the public and computer simulations that *model* this public would likely add a novel layer of unpredictability to the process. In the final section, this paper will briefly address such leverages of concrete cultural practices in relation to the Cultural Technique concept of swarm architecture.

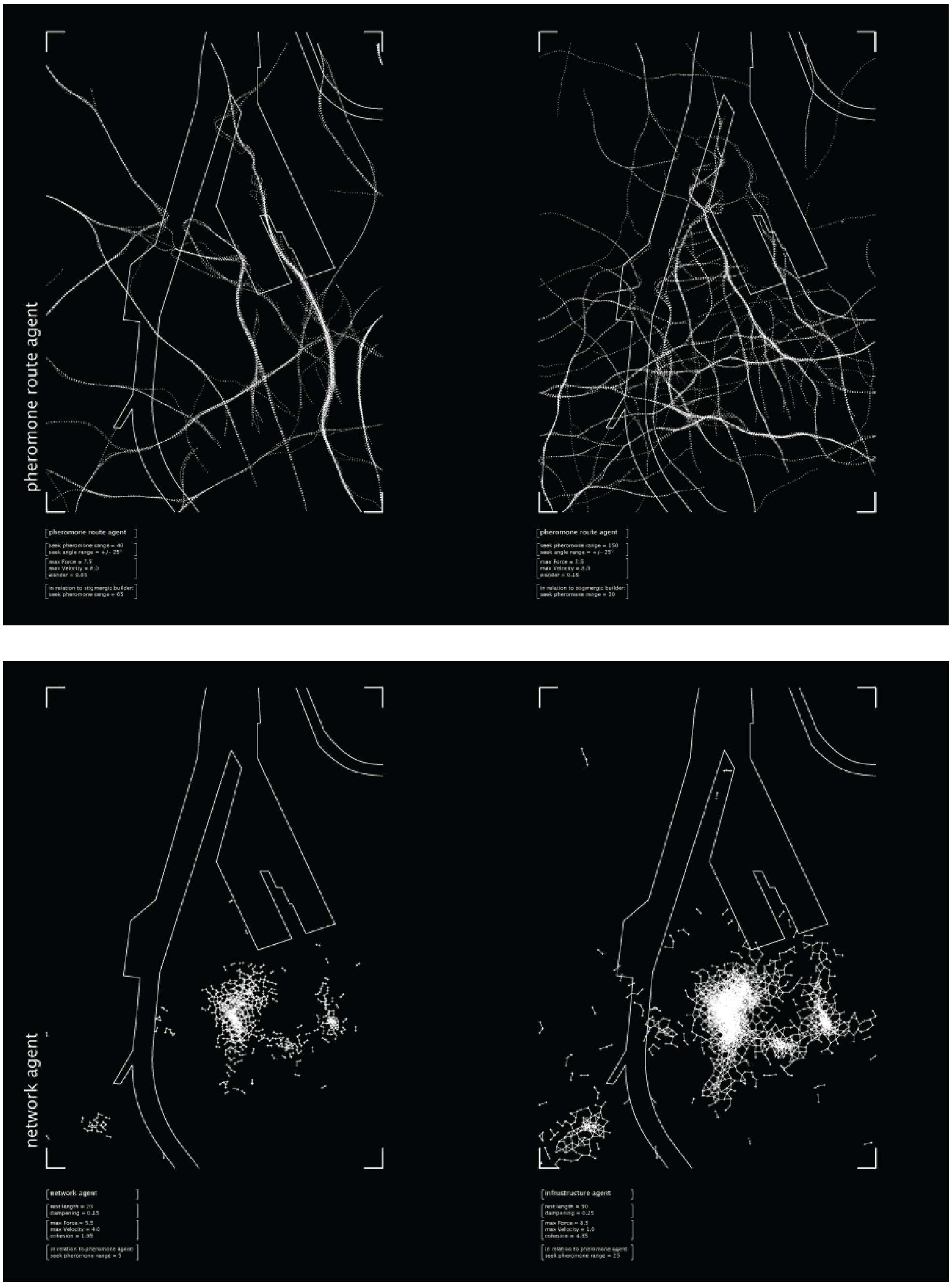

Fig. 2: Kokkugia's *Swarm Urbanism* Project (2009). The illustration shows a category of agents that aggregates matter to form in a stigmeric process, following rules of interaction similar to termite swarms. © Roland Snooks

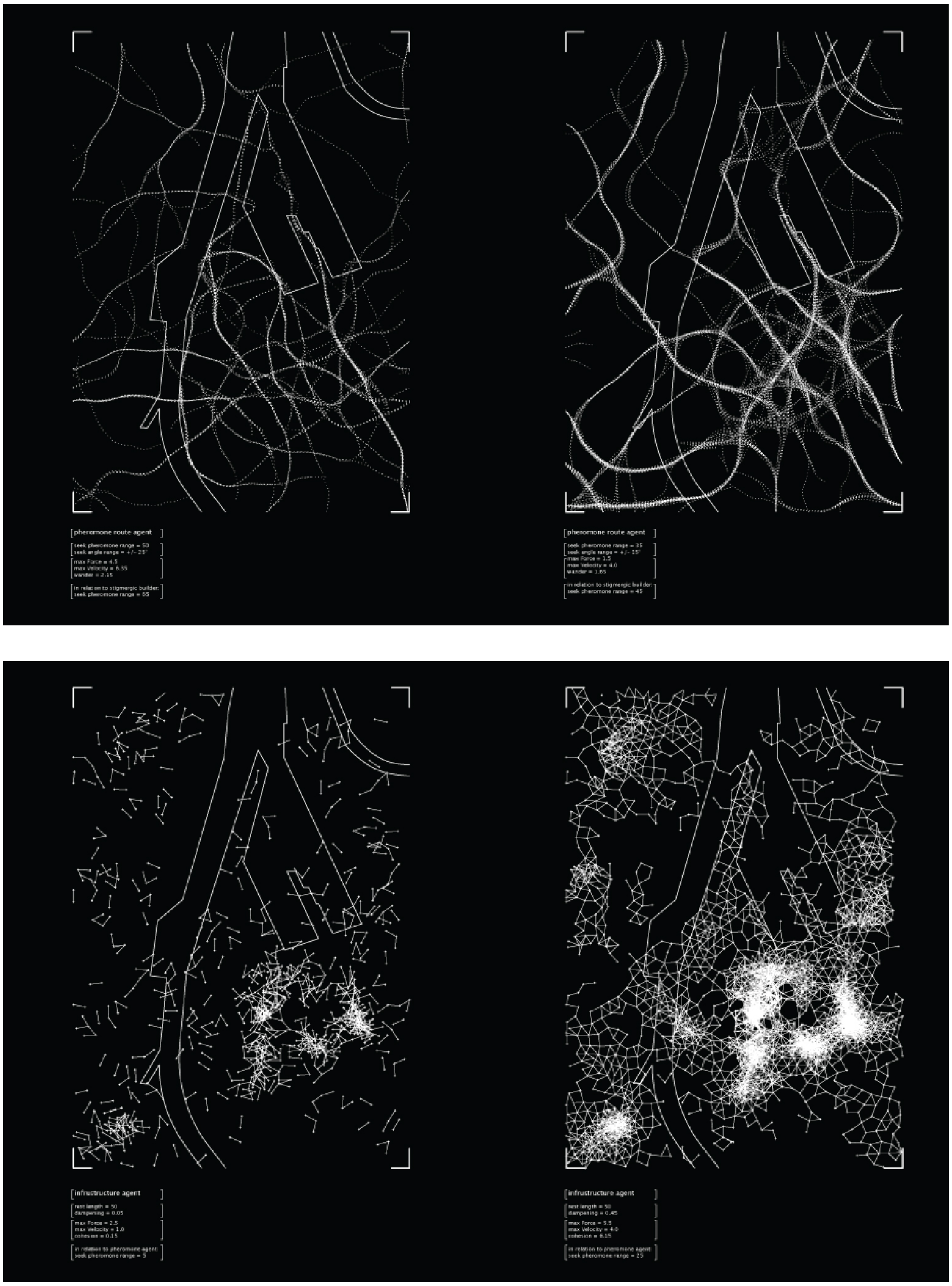

Fig. 3: Kokkugia's *Swarm Urbanism* Project (2009). The illustration shows a category of agents that connects various pathways to infrastructural and circular networks, using an algorithm based on the movement of slime mould. © Roland Snooks

Super-Connected Idiot Savants

From its inception, the concept of swarm architecture – apart from its computer-technological aspects – has also been closely tied to novel collaborative working practices that came about with the broadband-connected workforce of contemporary digital architects.[44] The collective intelligence of computational ABM systems seems to be repeated on the level of everyday architectural practices. This can be perceived in terms of computer-supported cooperative work (CSCW) software, and remote and dispersed co-working places. It becomes apparent in a mutable and open-ended design and construction process that allows for integrating feedback loops and adjustments to a constructor or customer's objectives during the ongoing realisation process of a project. It can likewise be seen in the object-oriented programming logic of architectural design and construction tools, whose usage can even be described as a stigmeric process in itself.[45] The issue, writes Oosterhuis, in perfect accordance with the relationality of SI technologies, is about 'not just being creative individuals, but building creative relationships', where the design process becomes an 'on-line and on-site testing […] in the swarm of flocking stakeholders'.[46] The computational cultural technique of swarming in SI and ABM outlined in the previous sections also penetrates the working cultures of contemporary architects. Architects whom Oosterhuis says would engage as 'hyper-conscious idiots [*sic*] savants' in a constant flux of information processes from project databases, and would act merely as 'assistants' to their self-organising computational tools, in other words, creating novel humanoid-technical hybrids.[47] Moreover, he insinuates a possible basic democratic function: by integrating open interfaces with the public, ordinary citizens could become participators in a 'design game', extending the cultural technique of swarming to a wider public.[48]

However, and in contrast to all the techno-euphoria that thrived in the early heydays of a swarming discourse, such socio-political implications remain a subject of continuing inquiry. First and foremost, an implicit question concerns Eugene Thacker's crucial disposition of *pattern* or *purpose* in SI. Thacker asks about the likelihood of swarm collectives defining a strategic agenda by their own means, in contrast to their unquestionable skills in reacting to changing, but pre-existing, environmental conditions.[49] Or, to put this more bluntly: to what extent are generative technologies in SI and ABM dependent on a top-down definition of *ex ante* boundary conditions and target functions, or *ex post* evaluations by experts? Are they not always embedded in other, more classical hierarchies of decision-making, and hence working as 'tactical' problem-solving tools rather than being able to generate original purposes? And secondly, one should carefully observe where exactly SI and ABM are employed in architectural, engineering or scientific processes, and how they correspond with other, neighbouring organisational formats and processes. How closely do certain idea models correspond with fabrication and manufacturing technologies? How exactly can the decisive relations and parameters for urban planning be evaluated?

Nevertheless, as this article has shown, SI and ABM applications can be perceived as cultural techniques well suited to handling complex planning problems as these emerge in architectural design. Swarm architecture takes advantage of the problem-solving intelligence that emerges from the self-organisational capacities of agent collectives and thus originates novel human-zoo-technical hybrids in the architectural design process. Computer graphics enable a visual comparison of various universal structures, both with respect to parameter adjustments within the rule sets of the simulations, and also in terms of empirical data taken from concrete architectural sites. The underlying function of this scenic knowledge is the act of *seeing in time*. Computer science is capable of animating mathematical models by endowing them

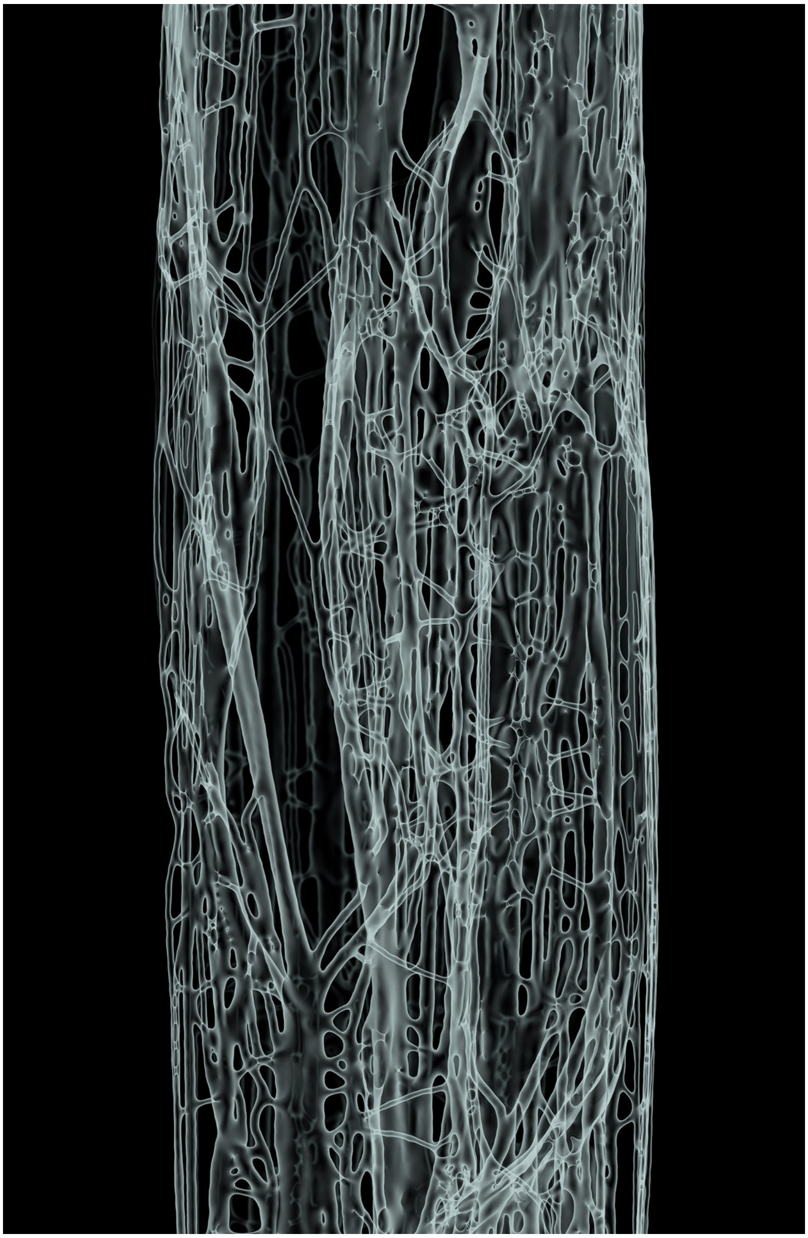

Fig. 4: Kokkugia's *Fibrous Tower 2* Project (2008). Exploration of ornamental, structural and spatial orders through an agent based algorithmic design methodology. © Roland Snooks.

with life in *run time* and exploiting certain gaming characteristics. And instead of coalescing into architectural master plans, they preserve the potential to generate a spectrum of opinions, viewpoints, and 'near-equilibriums'.

The extent to which the idiot savants of generative swarm architecture are able to claim the bottom-up potentialities and operational scope of their computational ABM for use in their working practices might also be a question of their environment: a participatory, 'basic-democratic' perspective – for instance, one enabled by virtually demonstrated dynamic architectural models of buildings or urban sites – might well be a very realistic part of generative architecture. It sounds more than feasible or necessary to integrate a critical public into the decision-making processes of urban planning, not least in order to moderate possible resistance. But this only seems to hold true as long as it takes place within a democratic society and not in those countries that have regrettably attracted a good number of the idiots (savants) of digital architecture in recent times.

Notes

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Biography

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A New Kind of Art [Based on Autonomous Collective Robotics]

Leonel Moura and Henrique Garcia Pereira

Introduction

We started working with robots as art performers around the turn of the century. Other artists/researchers in the realm of the art/technology interface have done similar experiments, and their endeavours were a potent stimulation for our work.[1] After the first trials, which relied on a bio-inspired ant algorithm running on a computer connected to a robotic arm, we decided to focus our research effort on the autonomy of the machine, i.e., the possibility of a machine creating its own drawings and paintings as a kind of *artificial creativity* stemming from *artificial intelligence*.[2]

Along these lines, *Artsbot*, a swarm of art producing robots created in 2003 (and updated to the present time), demonstrates that an interrelated group of robots can generate unique compositions that are independent from the human agent that starts the process.[3] To the best of our knowledge, *Artsbot* is the first experiment in which robotic art is understood as an emergent process based on a swarm of robots animated by a bio-inspired algorithm. By relinquishing control over the output, human creators can concentrate on 'making the artists that make the art'.[4]

It is worth noting that such machines should not be seen as mere tools or devices for predetermined human aesthetic creations, because they are (at least) partially autonomous, and the result of their actions is unpredictable. In addition, although randomness is an essential component of the process, the resulting artwork cannot be viewed as a mere random outcome, given that *recognisable* patterns emerge from a fuzzy background.[5]

The claim that the compositions produced by *Artsbot* represent a new kind of art – the art of semi-autonomous machines – may seem controversial in the context of mainstream concepts that consider art to be an exclusively human capacity. Actually, the underlying approach that drives this new kind of art is inscribed in the global advancement of robotics and artificial intelligence towards a greater autonomy of machines. Indeed, as usual, *Art* simply announces what is about to come.

Machine Art

With the rise of computers, *Digital Art* was the product of an artificial 'language' used to implement routines, trigger behaviours and run algorithms inside machines. The use of computers to make art was initially a subsidiary product of this new language. Artists used computers to generate processes and images that related mainly to the inner architecture of the machines. Through rules, protocols and algorithms, computers *created* processes and images as the result of complex calculations.

With the advent of machines as thinking devices able to perform tasks based on their own discretion, a particular form of intelligence coined *artificial intelligence* was developed, and 'computer art' took a new turn in which complexity is ubiquitous. Complexity gave rise to the possibility of simulating bio-inspired and emergent artificial systems. Hence it was possible to originate what is now known as *artificial life*; that is, *organisms* that live inside machines or explore the real world in the form of autonomous sensing robots.

In 2003, drawing on this fresh field of research, we proposed an adjustment of the principles of artificial life to elicit the production of artworks by a swarm of autonomous robots (*Artsbot*). We claim this endeavour to be a *new kind of art* because a) human creators deliberately relinquish control over their creations, and b) machines, when animated by a particular kind of *swarm intelligence*, generate a creativity of their own.

Technical Description of Each Artsbot Robot

The basic architecture of each *Artsbot* robot consists of three components: the sensors, the controller and the actuators. The sensors receive signals from the environment that are processed by the microcontroller in order to command the actuators. The RGB colour sensors, situated under the robot, can detect the entire palette of colours, but, due to the fact that *Artsbot* robots carry only two pens, colour detection is divided in just two ranges, 'warm' and 'cold'.[6] Proximity sensors assist robots to determine the area of the terrarium and to avoid collisions.[7] The actuators consist of three servomotors: two for the wheels and one to operate the pens. The controller is an on-board PIC.

Collective Behaviour

The case to be made by the proposed approach is that creativity emerges in the set of robots as a consequence of self-organisation, which is driven by their interaction with the environment. Actually, each robot's random walk – which occurs when the process starts – is only interrupted by the 'appeal' of a certain colour spot, trace or patch previously left on the canvas by another robot. Given that the robot only 'sees' a limited region of the canvas, if no colour is detected in that region, it continues on its way, putting down a mark of its passage on the canvas only if its random number generator produces a value that exceeds a given threshold. In the language of statistics, each one of the outcomes of the experiment is regarded as the realisation of a Random Function (RF). The RF is defined as the infinite set of dependent random variables $Z(u)$, one for each location u in a certain area A. In this case, the area A is the canvas, and the random variable is discrete, taking only three nominal colour values – warm, cold and white. The underlying feedback process leads to the spatial dependency of the random variables and explains why clusters are usually formed in most of the RF realisations. These realisations (paintings) are the mapping of the RF onto the canvas, depicting its fundamental hybrid structural/random constitutive nature.

The collective behaviour of the set of robots as it evolves on a canvas (the *terrarium* that limits the space of the experience) is governed by the gradual increase of the deviation-amplifying feedback mechanism that is the core of the programme governing the controller.

During the process, the robots show an evident behaviour change as a result of the appeal of colour, triggering a kind of excitement – which can be seen as a bifurcation – that does not occur during the initial phase corresponding to the random walk. Once a robot 'sees' a trace of a given colour – classified into the above-defined two classes (warm and cold) – the pen of the same colour class is dropped by the corresponding actuator, and consequently this colour class is accentuated in the vicinity of the trace that was previously left on the canvas.[8] As the interaction between robots is not direct, but driven by the positive feedback mechanism triggered by a signal left in the environment (this signal causes the robot to turn in the direction defined by the point where its sensor has detected the colour that corresponds to the received signal), we can posit that what is occurring when one robot reacts to what

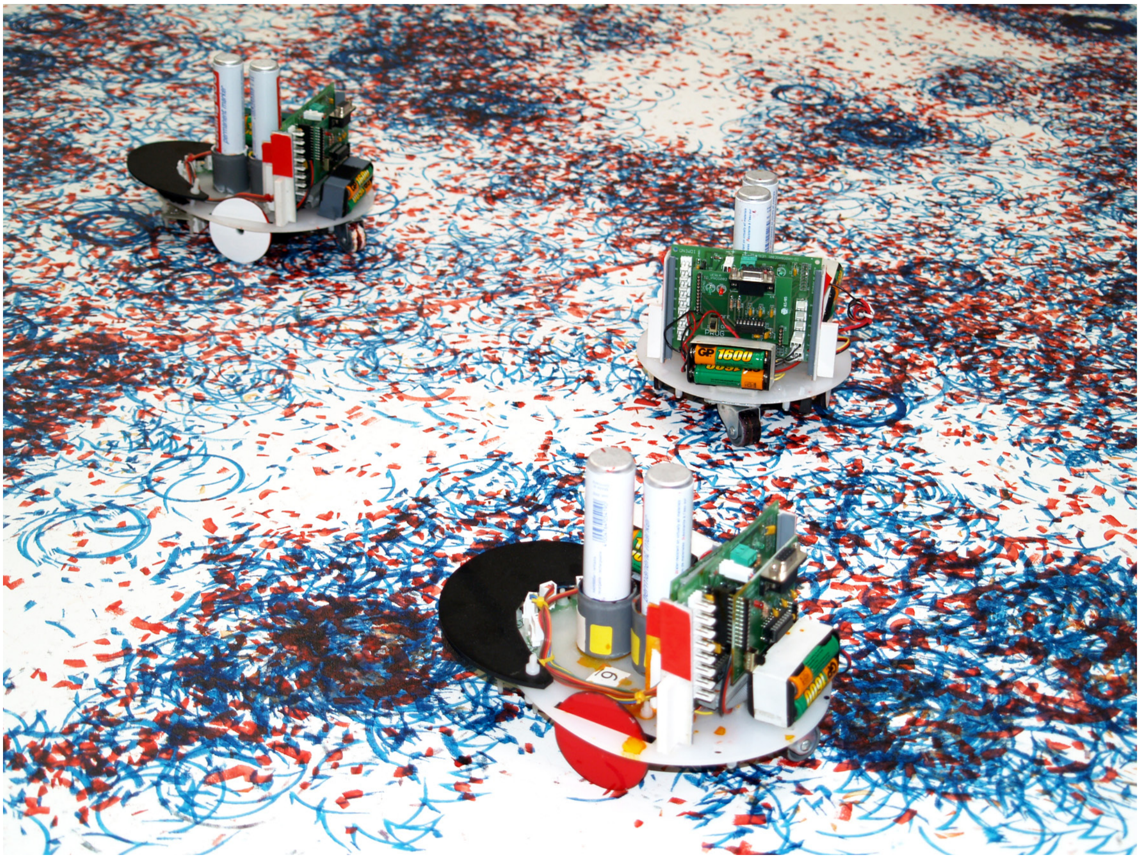

Fig. 1: Swarm of Artsbot robots working on a painting. © Author

other robots have previously done in the *terrarium* is a stigmergetic interaction between the robots.[9]

In fact, while developing *Artsbot*, we have tried to artificially reproduce an emergent behaviour similar to the natural behaviour of ants, bees, termites and other social insects. These insects communicate among themselves through chemical messages produced by the release of pheromones, which lead them to effect certain patterns of collective behaviour, such as following a trail, cleaning up, repairing and building nests, and defending, attacking or invading territory. Although pheromones are not the exclusive means of communication among these insects (the touch of antennas in ants or the dancing of bees are equally important), pheromonal language does produce complex cognition via bottom-up procedures. As previously stated, these procedures are obviously an indirect form of communication, coined stigmergy by Grassé, from the Greek stigma/sign and ergon/action.

Following these principles, we 'replaced' the pheromone with colour. The marks left by one robot trigger a pictorial action in another robot without any direct relation between them. Through this pseudo-random mechanism, abstract paintings are generated that reveal well-defined shapes and patterns. *Artsbot* creates abstract paintings that at first sight seem to be mere random doodles, but after careful observation, colour clusters and patterns become patent. When the coloured marks left by one robot are recognised, the other robots react to these by reinforcing certain colour spots. The process is thus anything but arbitrary.

Actually, what is crucial in the *Artsbot* experiment is the concept of *emergence* applied to a process that drives the swarm behaviour. Indeed, in the swarm behaviour, emergence arises when multiple agents that are interacting with each other and the environment in a rather haphazard way begin to generate order as a consequence of some form of *swarm intelligence*.[10] The process by which these mechanics can produce a novel behaviour, (quasi-) independent of the human that implements and starts the process, cannot be analytically modelled, but it should be understood as producing a new *gestalt*, along the lines of the complex dynamic theory, known commonly as 'chaos theory'.

For some authors, emergence is just a deterministic mechanism. According to this view, the set of rules or initial conditions determine the behaviour, and unpredictability is an emergent property of a system that may be predictable on a lower level of analysis. But, since no *complex system* can be understood by examining its individual parts, we claim that the deterministic view underestimates important components of the emergent process, which is the backbone of the collective behaviour produced by *Artsbot*, as displayed in the illustration.[11] [fig. 1]

Discussion and Conclusion

In our approach, the human artist creates the process but not the resulting drawing or painting.[12] Although the set of rules is changeable according to certain parameters, the most determining component of the process lies in the fact that the robots are driven by the data they gather from the environment. In *Artsbot*, our painting robots were designed to paint (not a specific painting but their own paintings). [fig. 2] Their creations stem from the machine's own interpretation of the world and not from its human description. No previous plan, fitness, aesthetic taste or artistic model is incorporated. Our robots are machines dedicated to their art.

Such an endeavour addresses some of the most critical ideas on art, robotics and artificial intelligence. According to the new advances in neurobiology, intelligence is understood as a basic feedback mechanism. If a system – any system – is able to respond to a certain stimulus in a way that

Fig. 2: 201004, 2004, acrylic on canvas, 75 x 75 cm.© Author

changes it or its environment, we can state that some sort of intelligence is present. 'Pure' intelligence is therefore something that does not need to refer to any kind of purpose, target or quantification. It may simply be an interactive mechanism of any kind, with no other objective than to process information and to react in accordance with available input characteristics.

Although the starting point of *Artsbot* was bio-inspiration (in particular, modelling social insects' emergent behaviour), its basic idea has evolved into constructing machines that are able to generate a new kind of art with a minimum of fitness constraints, optimisation parameters, or real life simulations. In this sense, we are not so much concerned with controlling manufacture as with taking the human out of the loop. The statement that machines can make art has implications far beyond the simple machine ability to mimic human behaviour. It opens the concept of art to all kinds of living forms, both natural and artificial.

Notes

1. Since the 1960s, with cybernetic art and in works by Nam June Paik, Jean Tinguely and others, artists have been using machines, and later robots, to produce art. Some were simply mechanical devices, but with the proliferation of computers they have become more and more 'intelligent' and increasingly autonomous. For an informed approach to the history of art and robots see Eduardo Kac, 'Origin and Development of Robotic Art', <http://www.ekac.org/roboticart.html> [accessed 19 April 2014]
2. This algorithm, coined ACO (Ant Colony Optimization), was developed by Marco Dorigo in 1992 in his PhD thesis. M. Dorigo, *Optimization, Learning, and Natural Algorithms*, Ph.D. dissertation (in Italian), Department of Electronics and Information, Milan Polytechnic, Italy, 1992.
3. The first results of the *Artsbot* project, including its rationale and underlying process, are reported in Leonel Moura and Henrique Garcia Pereira, 'Man+Robots, Symbiotic Art' (Villeurbane, France: Institut d'Art Contemporain, Collection Écrits d'artistes, 2004).
4. Leonel Moura, *Symbiotic Art Manifesto*, 2004, <http://www.leonelmoura.com/manifesto.html> [accessed 19 April 2014]
5. The concept of emergence as we view it is comprehensively addressed in S. Johnson, *Emergence: The Connected Lives of Ants, Brains, Cities, and Software* (New York: Scribner, 2001).
6. In our work, colour is the analogue to pheromone in ants.
7. The terrarium is the area in which the set of robots travels, executing the action of painting through the interdependence of their paths. It consists of a canvas lying on a horizontal surface and bounded by small (10 cm) vertical white walls that delimit the space where the robots can move.
8. This procedure is analogous to the case made by Herbert Simon where he describes the situation in which a moving agent reinforces known paths once previous choices have proved satisfying. Put forward in H. Simon, *The Sciences of the Artificial* (Cambridge, Mass.; London: MIT Press, 1996).
9. Stigmergy is the production of certain behaviours in agents as a consequence of the effects produced in the local environment by a previous action of other agents. It is worth noting that the biologist P. P. Grassé was the first researcher to develop this concept in the scope of his study of social insect behaviour, as reported in P. P. Grassé,'La réconstruction du nid et les coordinations inter-individuelles chez Bellicositermes Natalienses et cubitermes sp. La théorie de la stigmergie: Essai d'interpretation des termites constructeurs', *Insectes Sociaux, 6,* (1959), pp. 41-8.
10. For the development of this concept see Eric Bonabeau, Marco Dorigo and Guy Theraulaz, *Swarm Intelligence* (New York; Oxford: Oxford University Press, 1999).
11. This point is strongly made by Daniel Dennett on the basis of his concept of intentional emergence as the main property of complex systems. See D. Dennett,

‘Intentional Systems Theory’, in *Inside Art and Science* (Lisbon: LxXL, 2009), pp. 58-81.

12. This assertion embraces the approach discussed in Edward A. Shanken, ‘Art in the Information Age: Technology and Conceptual Art’, in *Invisible College: Reconsidering ‘Conceptual Art’*, ed. by Michael Corris (Cambridge: Cambridge UP, 2001).

Biography

Leonel Moura is an artist working in field of Artificial Intelligence and Robotics. One of his robots is on permanent display in the American Museum of Natural History, New York. He has created several Art Robots and a Robotarium: a kind of zoo for robots. Henrique Garcia Pereira is full professor at the Instituto Superior Técnico, Lisbon. His topics of research include Applied Statistics, Environmetrics and Epistemology. He has written over one hundred scientific papers and seven books.

Mind the Gap: Reconciling Formalism and Intuitionism in Computational Design Research

Zeynep Mennan

The relation between computational research and complexity can be argued to be one of mutual promotion and sustenance. If the twentieth century's task can be said to have reduced the methodological and phenomenological complexity of design problems, one may observe that recent computational research situated within the complexity paradigm reverses the task. The last century's preference for simplicity was mainly related to the shortcomings or impossibility of dealing with complexity using existing methods and tools. Computational research is now in possession of advanced and improved tools and methodologies that remedy such deficiencies, yet at the same time increase the complexity of design problems. Hence, the computational paradigm both creates and sustains complexity. Complexity bears a non-linear relation to information transmission and processing technologies: improved means and methods used in complexity management do not reduce but rather increase the complexity of design problems.

Complexity management is undeniably becoming a major issue in current computational research, sustaining and promoting naturalisation and formalisation as the two main operational forms encountered in the management of this complexity. In computational design research, as in other fields, the realisation of a growing complexity contributes to an extensive use of formal languages and quantitative/computational tools that rely increasingly on the translation of complex structures into a formal, natural idiom. In the field of architecture and design, technologies and methodologies which allow for such complex formal and structural explorations introduce a complete change of environment that is indicative of an interesting epistemic and methodological shift towards naturalisation and formalisation, which owe their success to their claim to a superior operational efficiency in the management of complexity.

A Process of Formalisation and Naturalisation

When discussing naturalisation, Jean-Michel Salanskis notes that the 'natural' is generally defined as that which has the power to evoke a scientific language of reference, whereas the 'non-natural' is defined as the 'spiritual' or the 'cultural', which evades the control of the scientific idiom.[1] Naturalisation and formalisation are both related to research within the analytical-cognitive sphere: naturalisation accounts for an objectification of cognitive and spiritual processes expressed in an ever-growing accuracy of translation into formal languages. The naturalisation project that finds its fulfilment in an increasing process of formalisation is oblivious to the phenomenological dimension, which is consistently ignored by cognitive science: 'basically arguing that this dimension is either irrelevant or inherently unreliable'.[2] Zahavi notes that by disregarding subjectivity and the first-person experiential perspective '[C]ognitive science faces what Joseph Levine has called "the explanatory gap": […] we seem to be unable to bridge the gap between the neurophysiological processes that we can describe and analyze scientifically from a third-person perspective, and the experiences that we are all familiar with from a first-person perspective.'[3]

The historical incompatibility of naturalistic and phenomenological traditions and the problem of their improbable reconciliation seems to be given a new direction and a new focus within the context of an increasing process of formalisation, launched by the complexity paradigm and endorsed in the field of computation. Current computational design research inscribes itself within such a project of naturalisation; it introduces a complete change of environment that substantially affects the ways in which we design and research, and it presents important implications at the methodological, epistemological and cognitive/perceptual levels.

Change in the Nature of the Support of Inscription

When considering the ontological and methodological implications and consequences that a naturalised environment presents for design research, reference can be made to a compelling discussion introduced by Bruno Bachimont in his epistemological study of the notion of a 'material hermeneutics', developed as a critique of formalism in artificial intelligence.[4] Bachimont's reflection departs from a consideration of the formal representation of information to question the cognitive or phenomenological contribution of formal calculation to knowledge, and the ways in which calculated representations induce a particular rationality.

Formalism, acting as the epistemological frame of reference for computation, is defined as a mode of reasoning preoccupied only with form, and disinterested in content and meaning. This mode of reasoning, which Bachimont defines as 'computational rationality', is a product of calculated representations that come in the form of numerical inscriptions. While formal inscriptions owe their success to their efficiency in calculation, Bachimont's discussion entails the problem of their intelligibility and interpretability, in other words, the possibility of their actual user attributing meaning to them.[5] To this end, Bachimont adopts a phenomenological approach, a mobilisation of Husserlian phenomenology to assert that all knowledge proceeds from a material support of inscription of which it is the interpretation: Bachimont poses the problematic of material hermeneutics as a philosophical reflection on the play between calculation and interpretation, drawing simultaneously on hermeneutics and the formal representations of knowledge to model the conditions for the intelligibility of formal inscriptions.[6]

The opposition of formal and natural languages constitutes the very interface of this problematisation: Bachimont notes that in natural languages meaning is appropriated by the reader, whereas formal languages dispose of the reader and the question of meaning. In his critique of computational reason, defined as the mode of thinking associated with numerical notations – in other words, a reasoning that is not preoccupied with meaning – Bachimont notes that material tools and instruments are assigned intellectual operations that unload the mind, letting it direct its interest to other tasks. These intellectual tasks then change character, and when the mind re-appropriates them, it is confronted with something different from what would have existed if it had performed the task itself.[7]

Extending this observation to the discussion of the constitution of knowledge as authorised by formal/numerical inscriptions, Bachimont concludes that the intellectual tools we use help us to think in different ways depending on their nature and properties, just as mechanical tools allow the fabrication of different material objects: this would mean that we can constitute new intellectual objects and elaborate new concepts that would remain inconceivable without such a numerical mediation.[8] But Bachimont

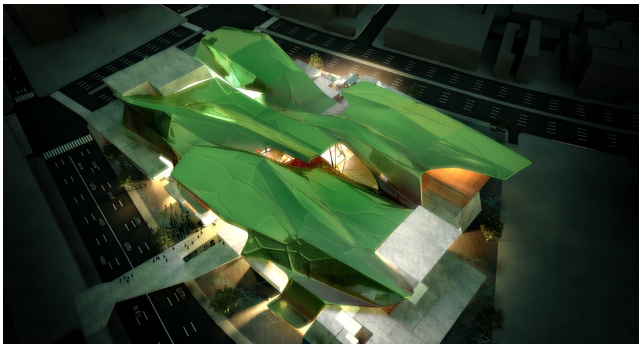

Fig. 1

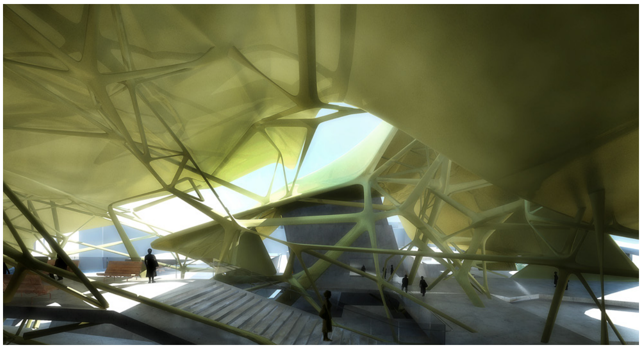

Fig. 2

Figs. 1-2: Taipei Performing Arts Centre, Taipei, Taiwan, 2008. Project Team: Roland Snooks (Design Director), Robert Stuart-Smith (Design Director), Brad Rothenberg, Elliot White, Matt Howard. © Studio Roland Snooks.

also notes that this does not necessarily lead to an extension of the cognitive field, it can also manifest itself as disorientation or a loss of meaning.[9]

A New Epistemic, Methodological and Representational Regime

Bachimont's discussion is crucial in its introduction of a new perspective through which the nature of the support that carries information is seen to induce a particular type of rationality. This means that the current preference in the computational paradigm for privileging formalist procedures and approaches in design and research would extend beyond being a matter of mere methodological choice on the grounds of efficiency, if it is agreed that the nature of the support is fundamentally affecting the ways we understand, conceptualise and interpret data.

The change in the nature of the supports is a consequence of an on-going process of naturalisation that operates through an enhancement of formalism and formalisation. These supports can be observed to have shifted from the conventional graphic medium of the drawing to the mathematical medium of calculation. Following Bachimont, this shift in the nature of notations and representations has also induced a shift from a graphic to a computational rationality. This condition, to which we have already become accustomed, has important implications that need to be questioned. Numerical notations expressed in a formal language have already gained a privileged place in current design research due to their efficiency in reducing complexity, equally fostered by the multi-disciplinary nature of such design research which requires the accessibility of formal representations across different fields and disciplines. Such supports may claim superior efficiency in complexity management, but the epistemological/ontological consequences of this shift have not yet been addressed or explored today by any design research agenda, either intentionally or otherwise.

If the conditions governing the intelligibility of formal notations vary with respect to the distinction Bachimont makes between a graphic and a computational rationality, then the increasing replacement of spatial analysis in architectural design by numerical analysis, and the corresponding displacement in the nature of representations, can be expected to indicate an interesting tension affecting both cognitive and interpretive faculties. When subjected to a numerical regime of interpretation, the qualities of phenomena are displaced and extended to new and unfamiliar kinds of supports, provided by a new, syntactical numerical language for representing design problems and solutions. The alienation which formal notations produce in architecture, grounded mainly in graphic rationality, is a problem that needs to be reflected upon within the context of naturalisation, and with respect to the changing nature of notations/representations on which knowledge is inscribed.[10]

Translation into a natural idiom brings forth a dematerialisation; this figures most intensely within the context of new technologies and leads to a virtualisation where the visible is quantified in a numerical language, thus becoming intangible to the senses. It can be noted that virtualisation, like formalisation, is also rendered operational within the context of naturalisation. As the limits of computation extend, the limits of sensory experience seem to shrink. Commenting upon the implications of the 'evanescent and mercurial' nature of digital forms on visual culture, Mario Carpo notes that 'in a digital production process one algorithm alone can generate an infinite number of mathematical functions as well as various forms or surfaces, all of which will share this invisible originating algorithm and, in most cases, carry some visible attribute that denotes their common matrix'.[11] Noting that the limits of computer programming are of an epistemic nature, and commenting on this common algorithmic matrix, Carpo argues that:

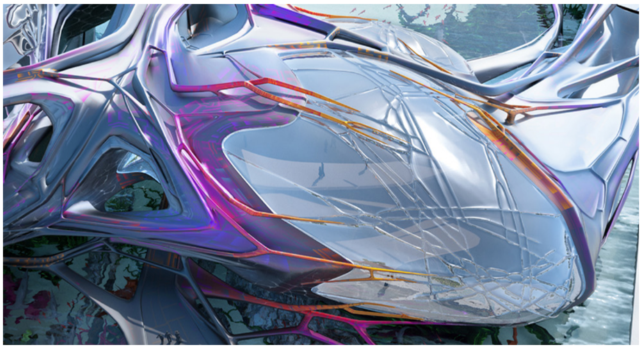

Fig. 3

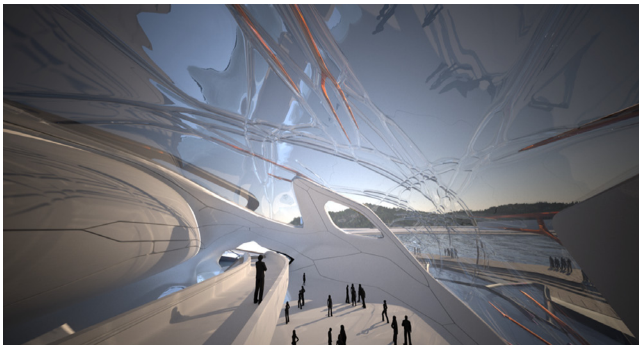

Fig. 4

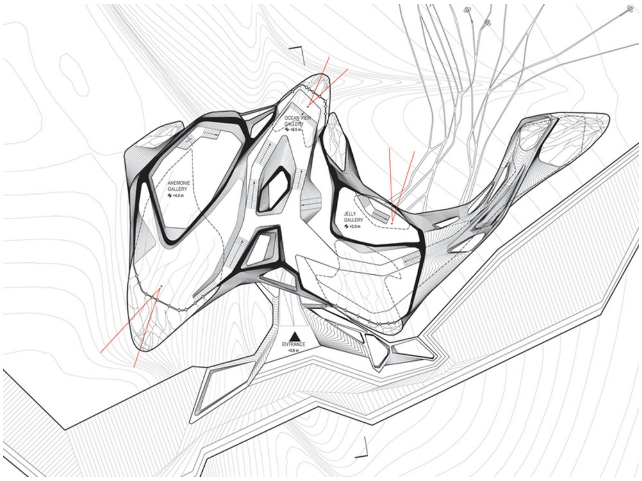

Fig. 5

Figs. 3-5: Yeosu Pavilion, Yeosu, South Korea, 2010. Design Directors: Roland Snooks and Tom Wiscombe. Project Team: Pablo Kohan, Fleet Hower, Ricardo Sosa (Studio Roland Snooks), David Stamatis, Chris Eskew, Brent Lucy, Graham Thompson, Zeynep Aksöz (Tom Wiscombe Design). © Studio Roland Snooks & Tom Wiscombe Design.

> This condition of reproducibility implies an analogous and corresponding condition of recognizability: all products of a non-standard series are different but they are also in some way similar to each other. What do they have in common? Technically, a mathematical algorithm; perceptually, however, it is difficult to say. The similarity between two visual forms is a mystery that no technology can quantify, no cognitive science can describe and no philosophy can define.[12]

The versatility and efficiency of formal supports seems to leave open the problem of the methodological and epistemological estrangement brought forth by the counter-intuitive nature of such supports.

Bachimont reminds us that if calculation reduces complexity through the exploration of a space that is unintelligible to graphic rationality, the problem of the complexity of calculation itself and the intelligibility of its results remain.[13] This is precisely how computation gives rise to a paradox, in the sense that it offers new tools whose efficiency and success are manifested by the very difficulties they create.[14] A surfeit of information that cannot be rendered intelligible brings to the fore the question of interpretation as a necessity. Material hermeneutics explores precisely this possibility of a material support's encounter with an interpretation. It attempts to supply the productivity and efficiency of formal representations combined with new interpretive practices that surpass conventional hermeneutical ones.

Reconciling Computational and Phenomenological Traditions

The notion of a 'naturalised interpretation' seems controversial at first when considered within the context of the distinction between the human and the natural sciences. However, several recent attempts have explored the expansion of hermeneutics beyond the realm of the human sciences to its application in empirical inquiries. Criticising the incompatibility of phenomenological and naturalistic traditions and the self-investment of hermeneutics exclusively in the human sciences, such an expansion of naturalistic interpretive practices takes place at the interface of hermeneutics and science.[15] Naturalistic interpretive practices look for a combination of the operational efficiency and the interpretability of formal representations to bring about the possibility of reconciling formalist productivity with phenomenological hermeneutics.

Petitot, Varela, Pachoud and Roy, editors of the seminal work on this issue, *Naturalizing Phenomenology: Issues in Contemporary Phenomenology and Cognitive Science*, engage in the mathematical reconstruction of phenomenological descriptions and claim that 'the vague morphological essences (including those pertaining to the experiential dimension) are amenable to a mathematical account'.[16] What is at stake in such an enterprise is to bridge the so-called 'explanatory gap' mentioned earlier. Representation in the form of a mathematical objectivity produces a disembodiment that brackets phenomenological interpretations of the design object. The formalism and the counter-intuitive nature of computational notations/representations thus leaves a gap between the formal layer and the layer of reality which it is attempting to replace: the intuitive layer of categories which structure this reality, a layer which is bypassed in formalist approaches that claim to be exhaustive.

The project of naturalising phenomenology is less an attempt to reconcile formalism and phenomenology than one that neutralises the phenomenological dimension by translating its contents into the very formal medium, which seems ill-suited to design research as observed so far. On the other hand, the turn towards materiality and practicality experienced in the last decades can be situated and assessed within the context of such a reconciliation between formal representations and the phenomenological grounds of design

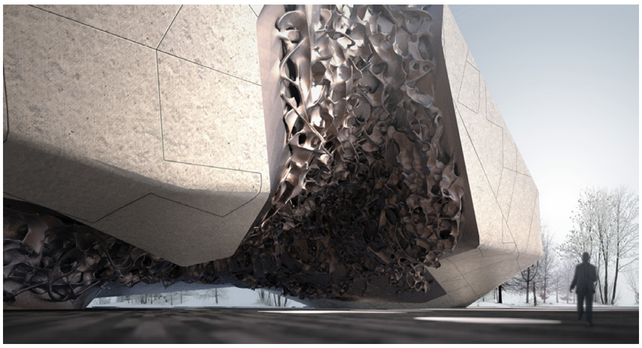

Fig. 6

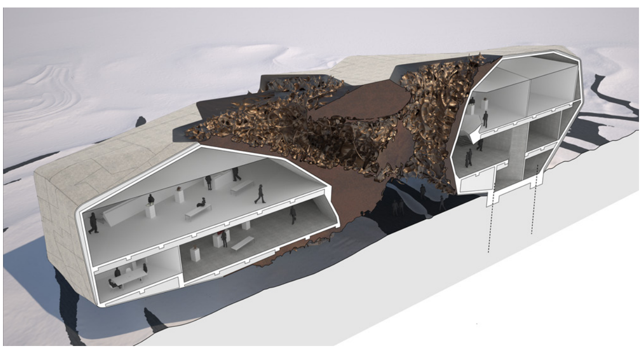

Fig. 7

Figs. 6-7: Babiy Yar Memorial, Kiev, Ukraine, 2010. Project Team: Roland Snooks (Design Director), Casey Rehm, Fleet Hower, Bryant Netter. © Studio Roland Snooks.

experimentations. The growing recourse to the physical/material prototype today clearly addresses the shortcomings of an absorption in heavy formalism, and comes as an indication of the necessity for dialogue between the world of computation and the more familiar and intuitive phenomenological sphere. Indeed, the structural logic and behaviour of new materials and forms are too complex to be anticipated and predicted within either the computational or physical medium alone. In this sense, the inseparability of computational and physical media in design research can be seen to be a logical consequence of the complexity of recent formal and structural explorations. These explorations are now manifesting an increasing interest in integrating forms of computational and material production.

Calculation leaves an incomplete space that cannot be saturated with information alone and waits to be filled with meaning and interpretation. A possible reconciliation between computational and phenomenological traditions could attempt to remedy the gap by reintroducing dimensions of subjectivity, intentionality and intuition into the medium of computation. The field of computational design research can only benefit from a call for an augmented phenomenological contribution to counteract its heavy formalism.[17]

Among the new generation of architects designing and researching within the realm of complex systems and exploring the potentials of generative design strategies, the work of Roland Snooks Studio and Kokkugia can be situated within the context of such a reconciliation. Roland Snooks directs a sustained critique on the subject of contemporary generative algorithms, the shortcomings of which are related to their inherently formalist logic: 'The inability to embed architectural decisions within a generative model remains a primary limitation of contemporary algorithmic processes, and substantially defers architectural intention to the evaluation of these generative models.'[18] Highlighting the gap between the formalist logic on which these algorithms operate and the architectural logic that is expected of them, Snooks notes that:

> It is the architect's role to adjust their parameters iteratively in an attempt to navigate their outcomes to a successful architectural result. An even more concerning trajectory within computational design is the prevalent ambition to remove the designer from this feedback loop, automating evaluation based on quantitative criteria, such as structure, in an attempt to optimise the engineering performance of buildings.[19]

Thus the work of Roland Snooks centres on the difficult task of embedding architectural design intention within generative algorithms in order to reinstate intention and subjectivity, and to affirm that the 'qualitative nuances, references, complexity, richness, and experience of architecture are beyond the capacity of numerically describable criteria'.[20] Insisting on the primacy of qualitative concerns over pragmatic ones, Snooks defines his design approach as one that 'works through the feedback of non-linear computational processes and subjective design decisions in creating an architecture […] defined by the strange characteristics that emerge from these processes'.[21] [figs. 1-2] Indeed, the very procedure used for this reconciliation has been named 'strange feedback', a key strategy used in Snooks' design research, and defined as 'a non-linear and inconsistent strategy of negotiation between generative and direct design procedures'.[22] 'Strange feedback' combines the bottom-up, emergent processes driven by computation with the top-down intentions and intuitive decision-making of the architect: 'This strategy is premised on feedback between algorithmic procedures and direct digital surface modelling, an attempt to maximise and hybridise the potential of each mode of design […] This interaction is both a shortcut for intuition and a mechanism for direct, subjective and non-systemic decisions.'[23]

A similar process of feedback between intuition and computation is advocated by Tom Wiscombe. Expressing his concerns about the impact of a heavy formalism on contemporary computational design, Wiscombe observes:

> [Advanced computation] has reached a kind of fervor, where technique is promoted over outcomes and effect […] you lose too much information when everything in an architectural problem has to be processed through an algorithm. Inputs are forced to become quantitative or otherwise abstract in order to be able to be computed, so it is not surprising that outputs are also anemic.[24]

A hybrid process, similar to 'strange feedback' is defined by Wiscombe as 'messy computation':

> There are such hardened camps now: you are either a bottom-up researcher or a top-down designer; you either experiment with means, or you design towards ends. A crossover term I like is "messy computation" – it is open-ended enough to allow you to be a designer but also capitalizes on the advantages of recursion and agency. Nothing is taboo that way. You pick and choose the right tool for the job, and more importantly, create custom workflows which jump around between techniques. It's a patchwork […] which I find very convenient, and happily, free of ideology.[25]

The apparent parallelisms between the approaches of Wiscombe and Snooks led to collaboration between Roland Snooks Studio and Tom Wiscombe Design in the design of a thematic pavilion for the Yeosu 2012 Expo, exploiting the shared sensibilities of the two architects. [figs. 3-5] Indeed, the practices of Roland Snooks and Tom Wiscombe distinguish themselves from many practices in contemporary algorithmic architecture in their articulation of subjective intention and reliance on intuition rather than placing confidence solely in the outcomes of computational procedures. In point of fact, the work of Roland Snooks Studio is said to have evolved in this direction from earlier work after an assertion that bottom-up techniques do not prove self-sustainable and that they need to be supplied with top-down procedures to achieve what Snooks calls 'a negotiated whole',[26] in which the two seemingly incompatible phenomenological and computational modes of design find themselves 'partly embedded within the generative algorithm as behaviors and partly in evaluation embedded within our intuition', and distributed within the work as self-organised and self-assigned intentions.[27] [figs. 6-7]

In this sense, 'strange feedback' is also impure, and this interaction of human intuition with computational logic is expected to lead to the emergence of 'something strange or potentially unique'.[28] This calls to mind the observation made by Bachimont that the mediation of a computational support could help us conceive and elaborate new intellectual tools and concepts if this support is made to meet an interpretation. This is precisely what is being explored in the practices observed: work within the computational environment imposes a shift to a new conceptual regime that at first produces alienation, but which then leads to discoveries/recoveries in new forms when this shift is able to be accommodated within a new interpretive regime. This would account for an augmentation of phenomenology rather than its naturalisation if it is agreed that the task is not the translation of phenomenological practices into naturalistic ones, but their integration into the naturalistic environment through a simultaneous articulation of formalist and intuitionist modes of design. This is a creative task of reconciliation that contemporary computational design research can answer with creative outcomes.

Notes

1. Jean-Michel Salanskis, *Naturaliser*, 2000, <http://jmsalanskis.free.fr/IMG/html/Naturaliser.html> [accessed 13 May 2005]

2. Dan Zahavi, ‘Phenomenology and the Project of Naturalization’ in *Phenomenology and the Cognitive Sciences* 3 (Netherlands: Kluwer Academic Publishers, 2004), p. 331.
3. Ibid., p. 332.
4. Bruno Bachimont, *Herméneutique matérielle et Artéfacture : Des machines qui pensent aux machines qui donnent à penser; Critique du formalisme en intelligence artificielle*. PhD thesis in epistemology. Paris, École Polytechnique, 1996, <http://www.utc.fr/~bachimon/Livresettheses.html> [accessed 10 June 2003]
5. Bruno Bachimont, ‘L’intelligence artificielle comme écriture dynamique: De la raison graphique à la raison computationnelle’, in *Au nom du sens,* ed. by J. Petitot (Paris: Grasset, 1999), pp. 290-319.
6. Bachimont, *Herméneutique matérielle et Artéfacture,* 1996.
7. Bruno Bachimont, ‘*Théorie du support: du support numérique à la raison computationnelle. Prolégomènes et critique*’, 2006, <http://www.utc.fr/~bachimon/Approchephilosophique.html> [accessed 10 June 2008]
8. Bachimont, 1999.
9. Bachimont, 1996.
10. For a discussion of an educational experiment on this issue, see: Zeynep Mennan, ‘Non Standardization Through Non-Visualization: Scripting the Dom-Ino House’ in *The Architecture Co-Laboratory: GameSetandMatch II, On Computer Games, Advanced Geometries and Digital Technologies*, ed. by Kas Oosterhuis and Lukas Feireiss (Rotterdam: Episode Publishers, 2006), pp. 234-41.
11. Mario Carpo, ‘*Pattern Recognition*’, 2006, <http://architettura.supereva.com/extended/20060305/index_en.htm#notes> [accessed 03 March 2007]
12. Carpo, 2006.
13. Bachimont, 1999.
14. Bachimont, 2006.
15. For new directions in phenomenology, cognitive science and hermeneutics see *Naturalizing Phenomenology: Issues in Contemporary Phenomenology and Cognitive Science*, ed. by Jean Petitot, Francisco J. Varela, Bernard Pachoud and Jean-Michel Roy (Stanford: Stanford University Press, 1999); Jean-Michel Salanskis, *L’hermeneutique formelle* (Paris: Editions du CNRS, 1991); Bruno Bachimont, 1996.
16. Cited in Zahavi, p. 335.
17. This position is akin to the one held by Harthong and Reeb in their epistemological discussion of intuitionism as a lighter variant of formalism rather than its epistemological counterpart. Jacques Harthong and George Reeb, ‘Intuitionnisme 84’, in *La Mathématique non Standard; Histoire, Philosophie, Dossier scientifique,* ed. by H. Barreau and J. Harthong (Paris: Editions du CNRS, 1989).
18. Roland Snooks, ‘*Behavioral Formation: Multi-Agent Algorithmic Design Strategies*’ (unpublished doctoral dissertation, RMIT University, 2014), p. 9.
19. Ibid.
20. Ibid., p. 53.
21. Ibid., p. 18.
22. Ibid., p. 103.
23. Ibid.
24. Ralf F. Broekman and Olaf Winkler in conversation with Tom Wiscombe, ‘A Higher Order of Organisational Complexity’ in *build urban architecture and design*, March 2010, <http://www.build-magazin.com/index.php/interviewpartner2010/items/tom-wiscombe.html> [accessed 10 June 2014]
25. Ibid.
26. Snooks, p. 15.
27. Ibid., p. 210.
28. Ibid., p. 105.

Biography

Zeynep Mennan is an architect, theorist and design critic. She has researched, published and lectured at major institutions and leading conferences in Europe, the USA and Australia. In 2003, she co-curated the ‘Non Standard Architectures’ exhibition at the Centre Georges Pompidou, Paris. Her fields of interest include the epistemology and aesthetics of computational design. At METU, she currently teaches architectural design as well as graduate and doctoral courses in architectural theory, research, epistemology and computational design theory.

Data Reshaped:
Literalism in the Age of Digital Design and Architectural Fabrication

Eran Neuman

The architectural discourse on 3D production has often asserted that processes of digital fabrication eliminate the need for conventional builders in architectural production.[1] Today, architects can design their ideas as a 3D virtual model and then fabricate the design without requiring conventional builders. Instead, they might only use fabrication tools such as 3D printers, CNC machines, laser cutters, robotic arms, and so forth to realise their ideas in material form, thus eliminating the involvement of builders in the process. This recalls the claim made by one of the principals of the Dutch architectural firm ONL, Kas Oosterhuis, who said that 'parametric detail is the core of a building process that takes the architect's data and produces it *directly,* a process we call "File to Factory"'.[2] Emphasising the direct nature of this process (the italics are in the original quote), Oosterhuis addressed his firm's fabrication of the Acoustic Barrier in Utrecht, the Netherlands. In this project, ONL attempted to directly fabricate building parts from the 3D virtual model without subjecting them to any abstraction or modification of the digital drawing. [fig. 1]

When Oosterhuis made the abovementioned statement shortly after the turn of the millennium, fabrication tools were not as advanced as they are today. In this forward-looking statement, Oosterhuis delineated tendencies within digital architectural research and development, even though the existing technologies were not yet able to provide solutions for the fabrication of emerging design ideas. Today, more than a decade later, technologies that allow a designer to send a file directly to a factory and have it fabricated without conventional builders or building techniques are increasing in number and availability. Enrico Dini's invention of the D-Shape, which allows the printing of 'full-size sandstone buildings to be made without human intervention, using a stereolithography 3-D printing process that requires only sand and special inorganic binder to operate', is a milestone in the effort to bypass conventional building techniques and develop a file-to-factory (FTF) fabrication process.[3] [fig. 2]

Like many of their contemporaries, Oosterhuis and Dini did not have an explicit ideology that called for the elimination of the middlemen, namely, the builders and fabricators who stood between the architect-designer and the end result. They only wanted to capitalise on digital design technologies and their ability to merge the design and fabrication processes. As Oosterhuis declared at an ACADIA conference in 2004, 'File to Factory refers to the seamless merging of the design process into fabrication. It involves direct transfer of data from 3D modelling software to a CNC (Computer Numerically Controlled) machine. It employs digital design and fabrication strategies based on computational concepts.'[4]

While not yet common as a building procedure, and mostly examined in unique projects and academic contexts, the merging of design and fabrication processes looks likely to become increasing widespread as technology continues to advance.

This is because the conflation of design and fabrication does not end with eliminating builders from the fabrication process. It also leads to a diminished need for other professionals, including engineers, during the design process, mainly because FTF implies a direct connection between architects and fabrication processes. The interim stages that traditionally were carried out by engineers are all integrated into one phase. Thus data and knowledge previously provided by engineers and other professionals must now be considered by architects in the initial design phase. Using advanced software, architects today are able to dynamically calculate a design's structural properties, plan a building's climatic attributes, or assess a structure's sustainable performance. A case in point: whereas before the advent of digital design, architects did not necessarily or directly address a design's structural aspects, but only understood its general structural principles, now they can calculate various aspects of its structural performance. As FTF design processes have become more comprehensive, architects are able to integrate more data during the design process – even before the design is completed and sent to a factory.

Advanced software tools that can perform various tasks were developed to assist architects in integrating knowledge and data that had previously been provided by builders or engineers. For instance, Dr. Clemens Preisinger of the University of Applied Arts in Vienna, together with the Vienna-based structural engineering office Bollinger-Grohmann-Scheider ZT GmbH, developed the software Karamba, a plug-in for Rhino and Grasshopper software. Karamba 'provides accurate analysis of spatial trusses and frames, and is easy to use for non-experts'.[5] Karamba has helped architects to calculate the structural properties of complex surfaces and morphologies. Previously, when using advanced software that enabled them to design multi-curved surfaces and 'oddly shaped' structures, architects did not always know whether their designs would contain all the structural properties necessary to enable the design to stand. Karamba has resolved this problem and allowed designers to dynamically calculate the structural properties of a work-in-progress during the design process itself. In this fashion, architects are able to develop complex morphology and eliminate doubts about whether it will hold together or not.

The mobilisation of data integration in the design process and the emergence of new digital fabrication technologies have led to a shift in the perception of architectural data. Before the advent of digital design processes, architects generated their designs in 2-D drawings and sketches, as well as 3D physical models. The drawings, sketches and models were representations of ideas, buildings or other elements that were meant to be realised at a later stage. Generally, these representations already integrated knowledge that was provided by other professionals, including engineers; nevertheless, all of them represented designs that would only be realised sometime in the future. Once completed, these representations were then used by builders to bring the designs into material being. Yet architectural representation could never integrate the full range of data necessary for the realisation of a design. Even if the representations were highly detailed, builders and fabricators always had to introduce more data in order to construct a design represented only in drawings and models.

With the advent of digital design processes and the elimination of builders from the realisation process, almost no new data is introduced between the design process and its realisation in the fabrication process. The allographic distance between notation and execution is annulled. As Oosterhuis claimed, the same data that is used for 3D virtual modelling is also used for fabrication so that design and fabrication both stem from the same data and are directly connected. In that respect, 3D virtual modelling does not represent a future realisation;

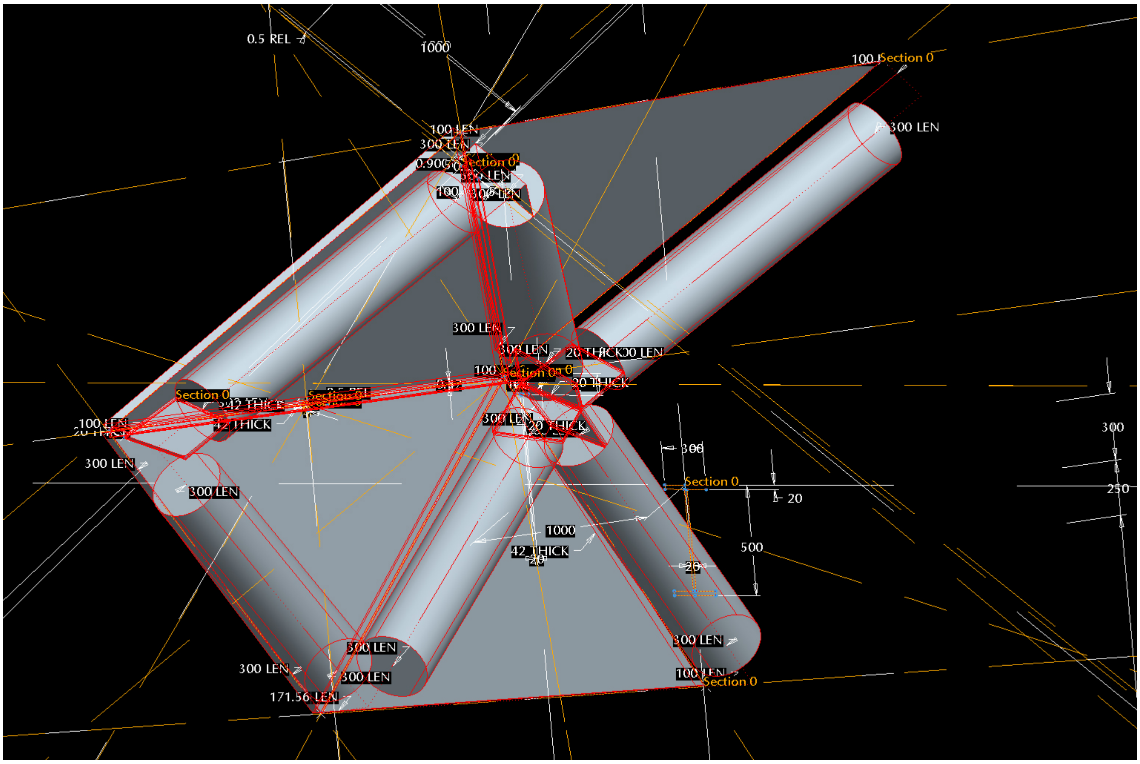

Fig. 1: ONL [Oosterhuis_Lénárd], Detail Sound Barrier, 2005. Image: © ONL

rather, it becomes one way of uttering data. The physical fabrication of the data is yet another utterance of the same data, this time in matter. Yet both refer to the same data, and, in that respect, they share a direct connection. In what follows, I propose to discuss the relationship between the various utterances of the same data as a process of literalisation of the architectural design process. Whereas prior to the emergence of digital media, and especially the FTF process, design processes drew upon representations, metaphors and analogies, with the advent of digital media and FTF, parts of the design process have become literal in relation to one another. The difference between utterances might be in the media (virtual vs. physical, visual vs. material), but their underlying data remains the same.

The conceptualisation of architectural production in terms of literalism could shed light on emerging procedures in digital design and fabrication. It could also assist both in creating defined processes for architectural design, based on understanding the literalisation of the digital design process, and in the perception of the architectural product, regardless of whether it is an object, space or environment. This essay attempts to establish the connections between digital design and literalism as a first step towards illuminating this emerging phenomenon.

Theories of Literalism

Theoretical discussions on literalism have been conducted in many disciplines, most prominently in linguistics, literature, the arts and philosophy, in relation to issues of representation, contextualism, directness and interpretation. In linguistics, whether in spoken or written language, literal expressions are considered to be non-symbolic utterances, existing outside of representation; they are perceived as standing only for themselves and not alluding to any external signification. A literal expression has its own singular signification, which is direct and particular.[6] Thus, literal expressions are not metaphorical, analogical or indexical; in other words, what you see is what you get.

The paradox that literal expressions posit is that language is a representational apparatus of communication that usually establishes some references to external significations. How, then, can literal expressions exist and function within language as linguistic structures, and yet at the same time be considered non-representational and non-symbolic? Over the years, linguists have tried to resolve this paradox while examining the ways in which literal expressions function in written and spoken language. They have proposed various approaches to reconcile this paradox, discussing the relations between literal expressions and interpretation, directness and contextualism.[7]

The reference to contextualism was the primary way to demonstrate that literal expressions do not establish relations with external significations. The French linguist and philosopher François Récanati was at the forefront in showing the non-contextual structure of literal expressions when he both defined them as utterances that do not need a context to be understood, and claimed that shifting a literal expression between contexts would not change its meaning.[8] This being so, literal expressions create a condition of parallelism. An uttered literal expression is parallel to its signification, and only to its signification. The phrase ‘this is this’, which is often associated with literalism, reflects the parallelism that literalism asserts. A literal expression incorporates two sides: one is the utterance and the other is the signification. The two sides are connected and equal to each other, but they function in separate realms: utterance exists in the realm of the signs that make up written or spoken language, while signification is located in the realm of understanding. They are connected in such a way that nothing can intervene between them.

Fig. 2: Enrico Dini, 3D Printer D-Shape. Image: © Shiro Studio

Literal expressions cannot be interpreted because they cannot absorb any additional data and create new signification. The French philosopher Paul Ricoeur claimed that interpretation indicates a surplus of meaning.[9] In order to interpret, one must take an expression and examine possible significations that, on the one hand, stem from the expression and, on the other hand, refer to notions external to the expression. The external signification is added to the expression, yet it must allude and adhere to the initial expression, otherwise the interpretation would be false. This is not so with literal expressions, because if a literal expression is one that stands for itself, it cannot include additional forms of data that would enlarge its meaning and signification. It can have only one signification.

Literature and the arts proposed a discussion on literalism parallel to the discourse in linguistics, in the course of which the media specificity of literature, painting, sculpture and other artistic forms generated new understandings of the topic. In literature, literalism concerned the literal understanding of a narrative that attempted to be direct and not metaphorical or analogical.[10] Thus realism was sometimes associated with literalism. Yet the main thrust of literalism in literature was to create an exact depiction of characters, events or situations without idealising them. This is because idealisation is a mechanism that operates consciously or unconsciously and leads to the misperception of conditions of reality. Consequently, reality is not seen in a literal fashion but as something else altogether.

In the arts, literalism has been associated with minimalism, more specifically with the geometric abstractionism of post-war American painting created by Frank Stella, Ellsworth Kelly and Kenneth Noland, as well as sculpture by Sol LeWitt, Dan Flavin and Donald Judd. In fact, minimalist art was often referred to as literal art, not only because of the minimalism of the artistic objects but also due to the directness of the expression.[11] In literal art, the material use is direct and does not create an illusion or an image that is not associated with the material itself. Similarly, the use of geometry does not attempt to reflect another meaning. The shape of the artwork is what constitutes the object and it does not try to become something else.

In architecture, literalism involved the discussion of objects and spaces that attempted to be literal. It included mainly architectural expressions that tried to avoid symbolism and representation. Therefore, the architectural discussion also associated literalism with minimalist architecture that tried to 'to strip everything down to its essential quality and achieve simplicity'.[12] The architecture of Tadao Ando, Luis Barragán, Alvaro Siza and, more recently, of Peter Zumthor, has often been referred to as a minimalist expression of architecture that can be associated with literalism. The minimalist characteristics of every work by these architects were seen as attempts to stay within the boundaries of each work in terms of itself alone, and not to expand it into other realms of signification.

In the theoretical discourse on architecture, literalism was discussed and defined in several ways. Colin Rowe was one of the pioneers in addressing the impact of literal expression on architecture when he wrote his critique on architectural production in the 1940s. For him, literalism was about ensuring the transparency of the object and the architectural space so that they would not conceal hidden agendas or ideas.[13] Since Rowe's seminal work, several architectural thinkers and scholars have addressed the topic; nevertheless, the writing on literalism has been sporadic and has not provided a wide-ranging overview of the topic. In recent years, Mark Linder has provided the most comprehensive discussion of architectural literalism. In several essays, and more extensively in his 2004 book, *Nothing Less than Literal: Architecture after Minimalism*, Linder proposes an historiographical account of literalism as he returns to the discussions on art and architecture of the 1950s and ’60s, especially the ideas put forth by Colin Rowe, Clement Greenberg, Michael Fried and Robert Smithson.[14] Although Linder does not explicitly attempt to provide a general theory of literalism, or one specifically related to architecture, throughout his discussion he clarifies several discrepancies within the ongoing discourse. These clarifications can be regarded as a basis for a theory on literalism in architecture.

For Linder, literalism was a reaction against modernism’s occupation with production, representation and the formalist tendencies that emerged in post-war architecture; it called for non-referential and autonomous architecture. Thus Linder also posits literalist expressions as objects or spatial conditions that stand for themselves, independent of representation. Nevertheless, this does not mean that literalist expressions are autonomous. Following the discussion of the American philosopher Stanley Cavell on literalism, and the long-running debates among linguists about the signification of literalism, contextualism and relativism in linguistic utterances, Linder clarifies one of the errors associated with literalism.[15] Literal expressions are not about autonomy. Unlike Peter Eisenman’s post-functionalist and self-referential architecture of the 1960s, literalist architecture does not attempt to maintain a position of autonomy in relation to other modes of expression.[16] It is not about disconnectedness and singularity. In his book, Linder expands on this matter and claims that ‘[l]iteralism is against interpretation and for application’.[17] Cavell best described this idea when he claimed that ‘literal usages can be *re*phrased but not *para*phrased’.[18] In other words, it is not that literal expressions try to be autonomous and cannot be mobilised or receive various utterances. Rather, in the movement of an expression from one format to another, it cannot be interpreted or receive additional data. On the contrary, it is supposed to maintain its integrity.

The non-interpretative trait of literal utterances does not imply that they are reductionist in nature. Indeed, Linder uses minimalist art objects and architectural designs to demonstrate the literalist tendencies of post-war artistic production. Nevertheless, his reference to minimalist art and architecture is related to the historical period that he examines, and to the artistic production of that time. His reference to minimalism does not imply that literal expressions are reduced solely to a consideration of the constituents that compose an expression. Rather, literal expressions allow a broader understanding of a phenomenon, but only within the scope that its constituents construct.

Linder views literalism as a mechanism that functions in a direct fashion, writing that ‘[l]iteralism locates the turning point when language or representation seems entirely adequate and direct, but also utterly inflexible and maddeningly indeterminate’.[19] For Linder, the directness of literalism is about rigidity, the maintenance of adequacy. Nevertheless, the directness of literalism can be seen in a more flexible way. This is because literalism implies that data can be transferred from one format to another, even without the addition of new data, which, in turn, implies that any utterances of the same data are interchangeably connected. Thus, the maintenance of adequacy does not require sameness or even similarity. It only requires the ability to interchange data among various media and formats without the addition of new data that would create new signification.

The process of expressing data in various formats raises a question in relation to literalism and contextualism. François Récanati argues that a literal expression cannot be contextual because the literal expression might be framed in a new light that could lead to its reinterpretation.[20] The question that might be raised here is whether a reformatting of an expression constitutes a new context that may or may not introduce new data to the expression.

Or to reiterate Cavell's idea, does the reformatting of data result in reshaping or paraphrasing it? In his writing, Linder does not address this question directly. Cavell, on the other hand, provides what can be seen as a resolution to the problem in his seminal book *Must We Mean What We Say?*, published in 1965. For Cavell, the paraphrasing of a poem does not maintain its 'core, essence and essential structure'.[21] The reformatting of data, which would be considered as reshaping the data, must maintain these conditions. The different usage of the terms 'literal' and 'literalism' in the various disciplines opens possibilities for understanding the phenomenon of literalisation in digital design processes. Whether addressed as an artistic historical phenomenon (Linder), or considered in relation to philosophy and interpretation, utterances or referentiality, literalism relates to data mobility and signification. In the following section, I will address the concept of literalism in relation to digital design procedures.

Digital Literalism

Rowe, Fried, Greenberg and Linder provided accounts of literalism in art and architecture, but these studies mostly considered artistic and architectural expressions, whether object-based or spatial, and not the processes that made them come about. Thus, they discussed the ways in which a literal expression stands for itself and functions self-referentially in its attempt to create signification and eliminate the shifting of data between expressions. A major reason for the concentration of post-war artistic and architectural literalist discourse on the object and space and their respective significations might be found in the difficulties that exist in shifting between media while maintaining the data as-is with regard to physical objects. How is one supposed to maintain data integrity while shifting between two media in a manual production? Can it be done by maintaining the form conveyed by the data and creating the same shape, only in different materials? Or is it done by maintaining the material use or performance and changing the form? After all, if on the one hand the reshaping of data is supposed to create a parallel expression, not a new one; on the other, the making of two objects that would be literal to one another does not mean a duplication of the same object. Indeed, maintaining all the aspects provided by that data in physical production would simply result in the creation of the same object twice.

With digital media, the maintenance of data integrity is somewhat easier. Digital media permits processes of data conversion and the transliteration of data that result in the encoding of the same data in different formats and the creation of variation. Defined as 'the process of producing meaningful information by collecting all items together and performing operations on them', data processing allows different software to refer to data and to present it according to its relevant format.[22] Indeed, in some cases the transformation of data from one format to another would bring about a loss of data in the encoding process. For example, in processes of transcoding – a conversion of one encoding format into a new format – some data is lost. Nevertheless, the data loss in transcoding is deliberate. It usually happens when seeking to reduce the size of a file and make it lighter in order to transfer the file more rapidly. In this case, parts of the data are omitted and not transferred. The representation of the new data with the new software would not be as detailed or as high a resolution as it could be.

Yet in other cases, mainly in processes of data conversion, the full data may be used. Data conversion is usually needed when specific software cannot encode data either for visual representation or for physical production. In pre-digital production, data that conveyed the ways in which an object – artistic or architectural – should be made could be stored in drawings, models, text or other formats. When a builder or a fabricator wanted to create the object or spatial design, they could refer to the stored data and execute it. In this process, builders or fabricators might add or subtract data according to their understanding of the initial data and the ways in which it was meant to be realised. The initial data was usually incomplete and did not represent the entire range of information necessary for the execution of a project.

Digital data, however, can be stored in many ways and then be converted into new formats that enable the data to be encoded. Once the data is converted into a new format that suits the software's encoding systems, this same data can be used and expressed in a new way. This process is called 'character encoding', meaning that characters of the data are replaced with new characters that can be deciphered by the software. The replacement of the characters does not have any semantic signification; it is only a syntactical procedure that transliterates one set of characters into another. In this process no data is lost. The data in its initial format and the data in its new format are identical. The encoding of the data and its representation might be different, but the inputs that made them come about are similar. As a result, both versions of the data can be used to create two different expressions that can be considered literal.

Another way to maintain data and create various utterances from the same data can be found in processes of design optimisation. Based on evolutionary algorithms, such as genetic algorithms, design optimisation seeks to create the best solution for any given problem. This involves searching within specific data for the elements that would help construct the best solution. However, this does not mean that data is lost in the iterative process; rather, it simply operates in a different manner. The full data is contained in each of the iterations, although only parts of the data are activated. In mathematics, this process is based on maximising or minimising a function. In these cases, a system usually chooses an input value that would best compute the desired function, either maximising or minimising the data's functionality. Nevertheless, the full data is at hand to create the next iteration. Evolutionary algorithms function similarly, and they create possibilities for data maximising and minimising, which produces an outcome in which the various iterations are interconnected and stem from the same data.

In architecture, ideas about data conversion, design optimisation, and the creation of variations that stem from the same data have been explored in the work of several architects, including Kas Oosterhuis, Marcos Novak, Greg Lynn and Matthias Kohler, and Fabio Gramazio. More specifically, when discussing the possibilities of topological design in architecture, the architectural discourse on digital design also addressed the issue of data mobility in relation to the creation of variations. As Mario Carpo noted in his 2011 book, *The Alphabet and the Algorithm*, Greg Lynn introduced the term 'differentiality' to architecture when he developed ideas about creating serial variations of a design.[23] Lynn posits that since topological design allows the creation of variations derived from the same data, the variations will be interconnected in their conception and production but different in their appearance. Lynn introduced this idea to differentiate in architecture between mass standardised fabrication and digital mass customised fabrication.[24] In mass standardised fabrication, variations cannot be made from the same data. The process ends with a unique fabrication process. In digital mass customisation, on the other hand, each of the produced items may be different yet stem from the same data. Lynn examined this possibility in several of his projects. For example, in the Flatware he designed in 2007, now part of the permanent collection of the Art Institute of Chicago, Lynn created a series of subtly varied metal sintered and silver-plated tableware prototypes that stem from the same data. [fig. 3]

Lynn's idea introduces the possibility of literalism in digital architecture. For Lynn, literalism exists

Fig. 3: Greg Lynn, GLForm, Flatware, 2007. Image courtesy of GLForm

Fig. 4: Open Source Architecture, the Hylomorphic Project, 2006, Mak Center, West Hollywood, CA, 2006. Image: © Joshua White, JW Pictures Inc.

between the objects since they stem from the same data. However, he does not limit his consideration simply to the objects and their interrelations. His work also addresses the process that brought the objects into being, since he relates to their conceptual and physical aspects in the way made possible by topological thinking and production. In that respect, Lynn's designs provide an opportunity for taking Linder's discourse a step further, since the literalism proposed by Lynn's production relates not only to the end result, in other words the designed object, or artistic or architectural expression, but also to the design process.

Thus literalism has been examined in relation to both the object and the design process, while taking into consideration the conversion between different media. We at Open Source Architecture examined this possibility in the Hylomorphic Project installation that was assembled at the Schindler House in West Hollywood as part of the 2006 Gen[H]ome Project exhibition.[25] [fig. 4] The installation was a structurally efficient 3D truss of linear members joined at nodes by pin connections. Its aim was to optimise material use while sustaining the installation's structural properties. The explorative part in relation to data maintenance occurred when the Los Angeles-based composer and sound artist Clay Chaplin used a converted form of the same data to compose a piece that was installed in the structure. In other words, the same data was used in two formats: built form and audio form.

The conversion of data in order to create similar objects in various media is another way to relate to literalism in digital design. As discussed earlier in this essay, Oosterhuis and other architectural researchers examined the possibility of FTF processes and the directness they established. In many ways, the researchers' ideas rely on the connectedness between the computer-aided design (CAD) and computer-aided manufacturing (CAM) processes developed by the inventor of stereolithography, Charles W. Hull, as early as 1984.[26] Hull sought a way to enable the printing of 3D objects. Throughout the development of stereolithography procedures, Hull attempted 'to harness the principles of computed generated graphics, combined with UV curable plastic and the like, to simultaneously execute CAD and CAM, and to produce 3-dimensional objects directly from computer instruction'.[27] The outcome was a connectedness between CAD and CAM data that allowed for the creation of a 3D printed object. Processes that started in graphic virtual presentations in CAD ended up in 3D objects that were generated directly from the CAD files. In stereolithography, the CAD and CAM procedures became literal to one another.

Towards a New Literalism

Over the years, the manifestations of literalism in art and architecture have varied according to contemporary cultural contexts and technological capabilities. With the advent of digital media, literalism once again acquired a new mode of manifestation that alludes to the cultural and technological circumstances of our time.[28] Thus, contemporary literal expressions and their signification differ considerably from pre-digital modes of literal expression, especially those of the 1960s and '70s. During those years, literal expressions concentrated mostly on the artistic and architectural object, its materiality and primary geometrical appearance. Therefore, literal expressions tried to avoid representation, and the concentration on the medium (matter, shape and form) of the artistic and architectural expressions became a means of articulating literalism.

This focus of post-war literal art and architectural objects and spaces on the respective media as the main mode of expression had several effects. In *Nothing Less than Literal*, Linder, following Michael Fried, discusses one of these effects, and posits that the intense preoccupation of post-war literal expressions with materiality and primary geometry is a reference to presence.[29] Literal objects of the post-war period both dealt conceptually with presence and conveyed an experience of presence. Several factors engender the strong feeling of presence that these objects convey. One is the minimalist aspect of the literal expressions. As objects that refer only to themselves, that do not have an external signification and cannot be interpreted, literal expressions limit the ability to let one's thoughts wander to other places after having engaged with these objects. Whereas other artistic and architectural expressions may allow the mind to wander, literal expression leads the subjects who experience it to focus on the direct expressions it conveys. They stay in the locus created by the literal expressions because these expressions do not permit mental displacement. This concentration enhances the feeling of presence.

In this respect, the non-representational aspects of the literal expressions make them into objects of the Real, in Lacanian terms. As Hal Foster suggested in his 1996 book, *The Return of the Real*, with minimalist art – or literal art, as he occasionally refers to it – 'it is precisely such metaphysical dualism of subject and object that minimalism seeks to overcome in phenomenological experience'.[30] The minimalist object and the subject that experiences it are both present and both literal. Literal expressions that are based in objects attempt to go beyond the representational and the symbolic, and, in so doing, create an effect of the Real.

Literalism today is not based on the artistic and architectural object or space but rather on design, production and fabrication processes. The ability to transliterate data, and to have data expressed in several ways that result in outcomes that would be literal to each other, shifts the notion of literalism from the object to the process. Unlike the literal objects of the 1960s and '70s, which were the site and locus of literalism and created its signification, objects of digital literalism are not the mechanisms that create its signification. Instead, the nature of the data and the process of its implementation become the mechanism that creates signification in literalism.

Digital literalism proposes a shift away from the singularity of the literal object and towards multiplicity. Whereas literalism in the 1960s and '70s concentrated on the object as a singular presentation of a literal signification that stemmed from and referred to the object itself, in the case of digital literalism, the ability to transliterate data and have it presented in several modes and media creates the conditions for multiplicity. If both the data that generates a digital process and the resulting architectural expression can be transliterated, then we can obtain multiple iterations of the same idea actualised in different media. The data and the process connect the various expressions and make them literal to each other. Such is the case with the digital presentation of the data for an architectural model in the virtual dimension, and its material realisation, for example, in print form. They are two iterations of the same data, yielding presentations of the data in multiple formats.

This recent shift of literalism from the object to data and processes is related to digital architecture's reference to emergence and evolution. The concentration of literalism in the artistic and architectural object and space in the 1960s and '70s refers to the philosophy of being: a phenomenological interest in presence. The object is there; it is finite and present. Today's interest in data and process, however, strongly alludes to digital architecture's discourse on becoming. In the last two decades, architects who deal with digital procedures have set algorithmic procedures, let the computer run its course, and allowed architecture to emerge out of the algorithmic process. Following Gilles Deleuze's philosophy of becoming, the architectural discourse opened a discussion about ideas such as flows, swarms and vectors as a means of creating dynamic, responsive and changeable architecture:

architecture that constantly emerges.[31] Similarly, the procedures of digital literalism in architecture are based on the rationale of emergence.

Thus, the concentration of digital literalism on processes may affect design methodology as a whole. The decline of the metaphor and analogies in design, along with the advent of the literalism proposed by digital procedures, require the architect to know how things are actually going to work. Metaphors and analogies do not necessarily convey the ways in which architecture might eventually operate. They are only suggestions for several modes of operation. Architectural metaphors and analogies refer to the signification of the design. Literalism, on the other hand, concentrates on the thing itself, and therefore it enfolds and delineates the ways in which architecture performs and operates – not only as a technical apparatus but also as a mechanism for experiencing architecture. As such, the shift from a metaphorical way of thought towards literalism in digital design requires architects to focus on the ways in which things work – in other words, to focus their attention on the process and performance of architecture.

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Biography

Eran Neuman is an architect and the head of the Azrieli School of Architecture, Tel Aviv University. His research focuses on digital design methodologies and culture, fabrication, and algorithmic design. Eran has lectured worldwide, including at Harvard University and Tongji University in Shanghai. Eran’s book, *Performalism: Form and Performance in Digital Architecture* (co-edited with Yasha Grobman), was published by Routledge in 2012.

Intersecting Knowledge Fields and Integrating Data-Driven Computational Design en Route to Performance-Oriented and Intensely Local Architectures

Michael U. Hensel and Søren S. Sørensen

Introduction

A continual problem of contemporary architecture is the question of how to negotiate the problem of architecture's increasing global homogenisation and the need to address local specificity. The question is how to unlock the performative capacities of architectures that are informed by their particular setting. In his seminal essay 'Towards a Critical Regionalism: Six Points for an Architecture of Resistance', Kenneth Frampton calls for a strategy that 'is to mediate the impact of universal civilisation with elements derived indirectly from the peculiarities of a particular place'.[1] Regarding the latter, Frampton stated that architecture which derives from this understanding 'may find its governing inspiration in such things as the range and quality of the local light, or in a tectonic derived from a peculiar structural mode, or in the topography of a given site'.[2] Yet regarding the former, Frampton cautions against an approach that exclusively emphasises optimised technology as this can limit designs 'either to the manipulation of elements predetermined by the imperatives of production, or to a kind of superficial masking' and thus lead to 'on the one hand, a so-called "high-tech" approach predicated exclusively upon production, and, on the other, the provision of a "compensatory façade" to cover up the harsh realities of this universal system'.[3] The concerns thus expressed seem equally acute today, and the question arises whether there are theoretical frameworks and design approaches and methods that can be deployed to arrive at the kind of mediation Frampton calls for in the search for spatially more enriched, and locally more specific, architectures.

One current approach in architecture focuses on a nascent notion of *performance*. As we have discussed elsewhere in detail, most of today's approaches to the question of performance originate from the form and function dialectic that in various guises has dominated architectural discourse since the 1930s and continues to divide architects chiefly into two camps.[4] The formal approach tends to focus on artistic aspects and invariably centres on the discrete architectural object, whereas the functional emphasis is frequently associated with science and, more specifically, with engineering and optimisation. Protagonists of the former criticise the latter for being too rigid and technocratic, while the latter criticise the former for being too elusive and superficial.

Thus, it seems necessary to seek ways of overcoming the equally artificial and superficial dichotomy between form and function, and to explore performative capacities instead, while avoiding a proclivity for single-minded optimisation. Our approach to this problem and to *Performance-Oriented Architecture*[5] is rooted in Actor Network Theory.[6] It ascribes the capacity of agency to non-human domains and elements. This approach focuses on the interrelation and interaction between four domains of agency: (i) the local physical environment, (ii) the local biological environment, and, (iii & iv) the spatial and material organisation complex that constitutes architecture and the built environment, including the cultural and technological aspects this encompasses. This approach is based on incorporating local conditions as drivers in defining the interaction of architectures with their settings and hence as the key input for generating architectural designs. Our objective is therefore to seek approaches to the question of the 'local' in architecture that are fundamentally performance-oriented and geared towards locally embedded or *non-discrete* architectures, as well as to promote their aggregation into the urban fabric and their articulation by way of locally specific tectonics. This can be accomplished by what we term 'informed non-standard' architectures. These encompass so-called non-standard architectural solutions that are informed from the onset of the design process by data sets pertaining to the specific local conditions and setting of a given architecture.[7]

To achieve this objective necessitates both conceptual and methodological inquiries and approaches. The latter emphasise the integration of advanced computational design aspects and methods, and have led to the implementation of the Advanced Computational Design Laboratory (ACDL) at the Oslo School of Architecture and Design (AHO). In this context, a range of computational data-driven design methods are explored, developed and integrated which facilitate generative design processes fed by a range of context-specific and often real-time data sets. These processes are tested in the specific design and built efforts at Research Center for Architecture and Tectonics (RCAT) – in particular in the context of the Scarcity and Creativity Studio – and serve as both proof of concept and the context for analyses of a wide range of architectural and environmental interactions.[8]

RCAT's and ACDL's approach to *Performance-Oriented Architecture* pursues integrated spatial and material strategies in order to articulate the built environment, to respond to and modulate local climate and microclimate, to provide for a broad range of spaces for condition-related patterns of use and habitation, and also to integrate with local ecosystems. The understanding that the spatial and material organisation of a given architecture plays the key role in its interaction with its specific setting motivates this approach.[9] In this context, emphasis is placed both on architectural designs and on supplementing the pre-existing built environment with auxiliary architectures so as to enhance its performative capacities.

On a conceptual and pragmatic level, the attempt to activate the spatial and material organisation of architecture may be addressed by way of *tectonics*, as pursued by Semper and Frampton. Frampton restated the four elements of architecture that Semper had proposed as quintessential historical elements of architecture, defining them thus: (i) earthwork, (ii) the hearth, (iii) framework/roof, and (iv) lightweight enclosing membrane.[10] Moreover, Frampton maintained Semper's classification of dividing 'the building crafts into two fundamental procedures: the *tectonics* of the frame, in which lightweight, linear components are assembled so as to encompass a spatial matrix, and the *stereotomics* of the earthworks, wherein mass and volume are conjointly formed through the repetitious piling of heavy mass elements'.[11] Evidently, the proportioning between these procedures and elements was entirely dependent on, and attuned to, local conditions, as both Semper and Frampton pointed out. Frampton articulated and confirmed Semper's understanding as follows:

> [A]ccording to climate, custom, and available material the respective roles played by tectonic and stereotomic form vary considerably, so that the primal dwelling passes from a condition in which the earthwork is reduced to point foundations […] to a situation in which stereotomic walls are extended horizontally to become floors and roofs.[12]

Today's globalisation processes render such differentiation progressively insignificant, given the vastly increasing global mass of reinforced concrete which constitutes a considerable legacy for the future built environment, and the steel frames and glass façades that hold sway in mid- to high-rise urban fabric, in disregard of local conditions. Differences in local climate, for instance, are today by and large balanced by way of technological prostheses added to spatially and materially homogenous and locally indifferent architectures. In order to address this problematic and its intended impact upon the bulk of architecture, it is of interest to link a differentiated understanding of *tectonics* and *stereotomics* informed by local conditions as drivers of difference, with the notion of informed, non-standard architecture that affords a broad, performative, spatial and material repertoire. It is necessary, however, to move the primary emphasis of so-called non-standard architecture away from idiosyncratic formal expression and toward architectures that are intensively embedded in their local environment. This entails a shift away from the design of discrete architectures that stand out from their setting by way of celebrating their superficial difference, towards one that is *non-discrete*. This gives rise to the possibility of articulating an *informed non-standard* architecture that is non-discrete, embedded within its local setting, and produced using local means and resources.

The proposed notion of non-discrete architecture not only entails spatial and material embeddedness, but also expands to include extended environmental conditions and conditioning, as well as locally specific cultural practices of using and appropriating space.[13] With an understanding of architecture that extends beyond the physical object and towards object-environment interaction across scales and time, the perpetual transformation of the local environment and the underlying dynamics and processes gain importance. The questions that arise from these considerations are (i) how to methodologically underpin this approach by way of integrated data-driven informed design processes, and (ii) how to select, develop and integrate the various elements that are to make up the methodological framework.

Lines of Inquiry

ACDL's methodological approach to performance-oriented and locally specific architectures integrates recursive processes that combine (i) design generation and analysis based on locally specific design benchmarks with (ii) context-specific life-data input and (iii) materialisation-oriented processes based on locally available resources. These processes are deployed on various scales, ranging from the scale of minute material organisation to the scale of urban fabric.

Integrated generative and analytical computational methods facilitate the production and visualisation of nuanced conditions that develop over time and may underlie complex, multi-faceted design processes. These involve the human subject, the environment, and the spatial and material organisation of architectures as active agents in the production and utilisation of heterogeneous space. In so doing, these methods go beyond merely generating the design of discrete architectural objects and instead consider the wider scope of agency and processes by extending the scale and timeline of consideration beyond the materialisation of an intended design. On the methodological level, this entails an operational matrix of integrated, data-driven methods with various feedbacks. This matrix has multiple entry points relative to design intentions, involved processes, and domains of agency, as well as particular requirements regarding design and scale-related aspects. ACDL currently pursues four lines of inquiry:

1. A first level of architectural and environmental interaction involves the response to, and modulation of, the local physical environment, including the

local climate.[14] Frequently, design processes that engage locally specific climate conditions, such as, for instance, solar impact analyses, employ off-the-shelf analytical software that operates on average conditions and averaged output. Here, one may extend the toolset so that life data can deliver the full range of conditions, including peak conditions. At ACDL, networks of weather stations are configured and utilised in order to analyse local climate variation, which can be dramatic in Norway due to its different climate zones, altitude differences and significant local terrain variations. In a second step, the life data collected from the sensor network is fed into the generative design process and the outcomes are evaluated in relation to the full range of local climate conditions. Wherever possible, we pursue design and built activities that can provide, in context, measurements on the architectural and environmental interaction.[15]

2. Materialisation and material performance-oriented design processes are developed along several trajectories at ACDL. The first trajectory concerns the aspect and processes of materialisation. Wherever computer-aided fabrication technologies are locally available, they are incorporated as design-informing criteria and parameters. Wherever this is not the case, locally available craftsmanship delivers driving criteria and parameters. At any rate, locally available material is key to determining context-specific input, together with considerations concerning locally available technology and skills. Secondly, the question of material and materialisation is centrally related to that of environmental performance and the modulation of the local microclimate, and thus feeds back to the question of interaction between architecture and local setting.[16] In so doing, this line of inquiry directly feeds back into line 1.

3. Moving upwards in scale, the aggregation of embedded or non-discrete architectures into the urban fabric is investigated in order to develop low-rise densification models that are integrated with the local physical and biological environment. This line of inquiry has only just commenced and will for now be omitted from the discussion below.

4. Most types of visualisation in architecture foreground the architectural object. Analysis-oriented visualisation frequently emphasises the interaction between the architectural object(s) and a range of dynamic conditions. However, the exploration of spatial aspects, conditions and dynamics requires a more immersive kind of visualisation. In order to help visualise these elements in the different stages of the design process, and to facilitate communication in interdisciplinary design teams, ACDL develops and extensively deploys augmented and virtual reality visualisation methods. Tools are often developed by the students, frequently based on components that are in the public domain and freely available. Emphasis is placed on the affordability of hardware and software resources for this purpose, so that these are available to all students and researchers.

Each line of inquiry is based on an integration of different methods and tools. Yet from an overarching perspective, the question arises of how to accomplish a conceptual integration across all lines of inquiry. Below, lines 1, 2 and 4 of the inquiry are discussed in terms of their intent and methodological approach, followed by a discussion of questions pertaining to a tangible visualisation of data to support the design team and the design process.

Staging Interaction Through Data-Driven Design Processes

The first line of inquiry focuses on utilising data in the design process that pertains to the local environment, and on coupling this information with use and habitation potential. At RCAT and ACDL, this is done in the context of master-level studios and workshops, as well as in master thesis projects and research in the form of design PhD dissertations.

Frequently, these efforts link the notions of non-standard architecture (where breaking symmetry is essential in responding to specific local conditions) with heterogeneous spatial and environmental conditioning, and employ the building envelope and its articulation and multiplication as a spatial device and environmental modulator. In this context, one set of experiments focused on examining Eladio Dieste's Gaussian vaults and freestanding vaults as exploratory case studies aimed towards knowledge discovery, and as concept and method building, or, alternatively, as proof of concept.[17] The Gaussian vaults were modelled in associative modelling software so as to enable design solutions that no longer rely on a strict axial symmetry for the uniformly repeated vaults that generally characterise brick and masonry vaults. The breaking of symmetry enables a more nuanced orientation of the arrays of geometrically varied vaults towards environmental conditions such as sun path and angle, prevailing wind directions, movement trajectories, and so on, while at the same time retaining the specific integrated structural and geometric shell characteristics.

These experiments entail scales ranging from the extended area that is climatically and programmatically affected by the resulting architecture, down to the detailed brick arrangement, so as to ensure that the modified designs comply with the underlying structural form and principle and are also buildable. Following from this, the next set of experiments combined the first and second line of inquiry: context specific input (in this case, predominately earthquake impact and ground conditions) and materialisation oriented processes. Organised as either exploratory studies or proof-of-concept in different conditions, a single-brick layer, non-reinforced shell typology entitled 'Nested Catenaries' was developed by Sunguroğlu Hensel, various versions of which were built and analysed.[18] [fig. 1]

The experiments commenced with physical form-finding methods that were progressively supplemented with computational form-finding methods in an associative modelling environment. The response of the designs to local conditions was initially limited to structural aspects and available materials, such as the Nested Catenaries structure in the Open City in Ritoque, Chile, which needs to withstand severe earthquake and gale force wind impact, and was made out of a low quality local brick and corresponding mortar. In the following steps, the environmental modulation capacity of the system is examined. This research works bottom-up from initial, singular interactions to increasingly complex interdependencies, and from a nested structural system to an integrated nested spatial and environmental system. Each level of inquiry is facilitated by interdisciplinary collaboration that also involves the integration of methods and tools across disciplines.

Another set of experiments combined the first and fourth lines of inquiry: context specific data-driven process – in particular, life data recorded on site – and advanced visualisation as feedback. Light structures, such as textile membrane systems, offer an effective and feasible way to provide auxiliary architectures for existing buildings with insufficient space for different kinds of use, or insufficient climatic performance.[19] To tackle this appropriately, local weather conditions need to be measured and fed into the design process. The experiments focused on the design of auxiliary architectures of this kind for a series of public urban spaces in Oslo. Physical form-finding methods and computational associative modelling, local weather data input based on custom-made weather stations, and AR/VR visualisation tools all played a key role in the design process. [fig. 2] Large data sets and complex data interaction are hard to handle for most people, and extended utilisation of data sets in the architectural design process reinforces the need for information to be tangible, hence the use of spatial visualisation. In the context of this studio, efforts commenced to build custom-made weather

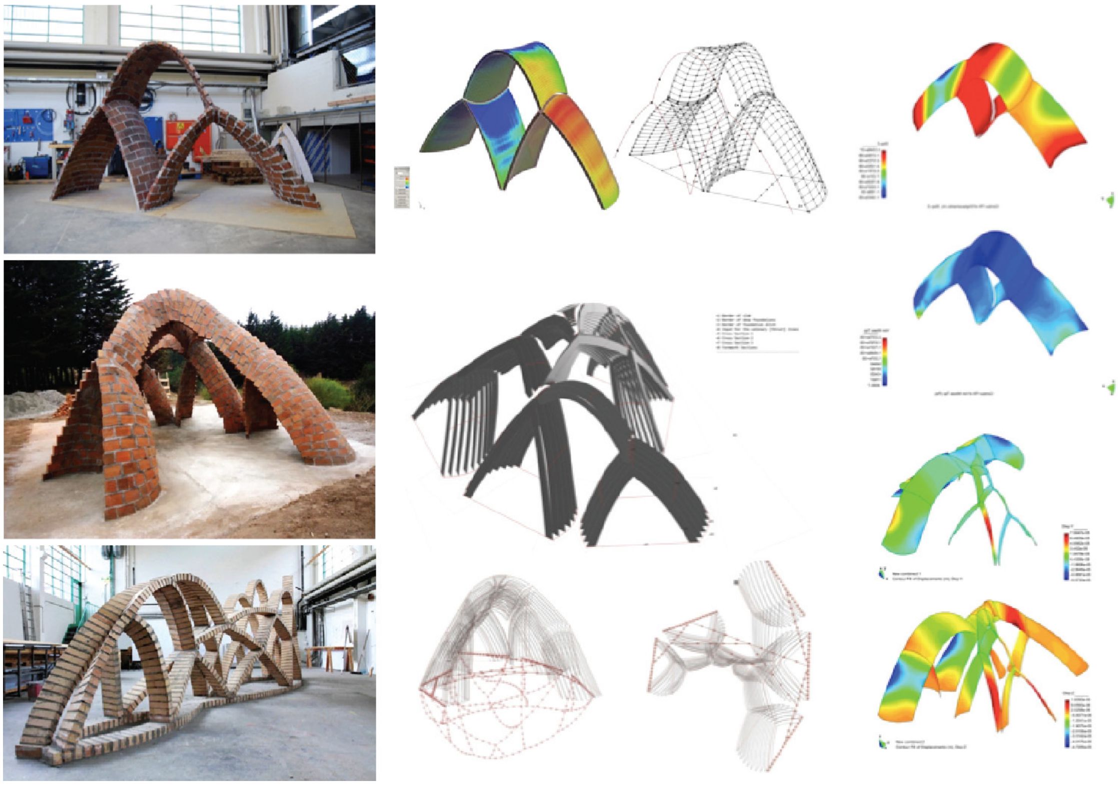

Fig. 1: Design and built projects as Proof of Concept for recursive data-driven computational design processes. Top to bottom: Three stages of development of the Nested Catenaries system as single layer non-reinforced brick arches and shells. © Defne Sunguroğlu Hensel.

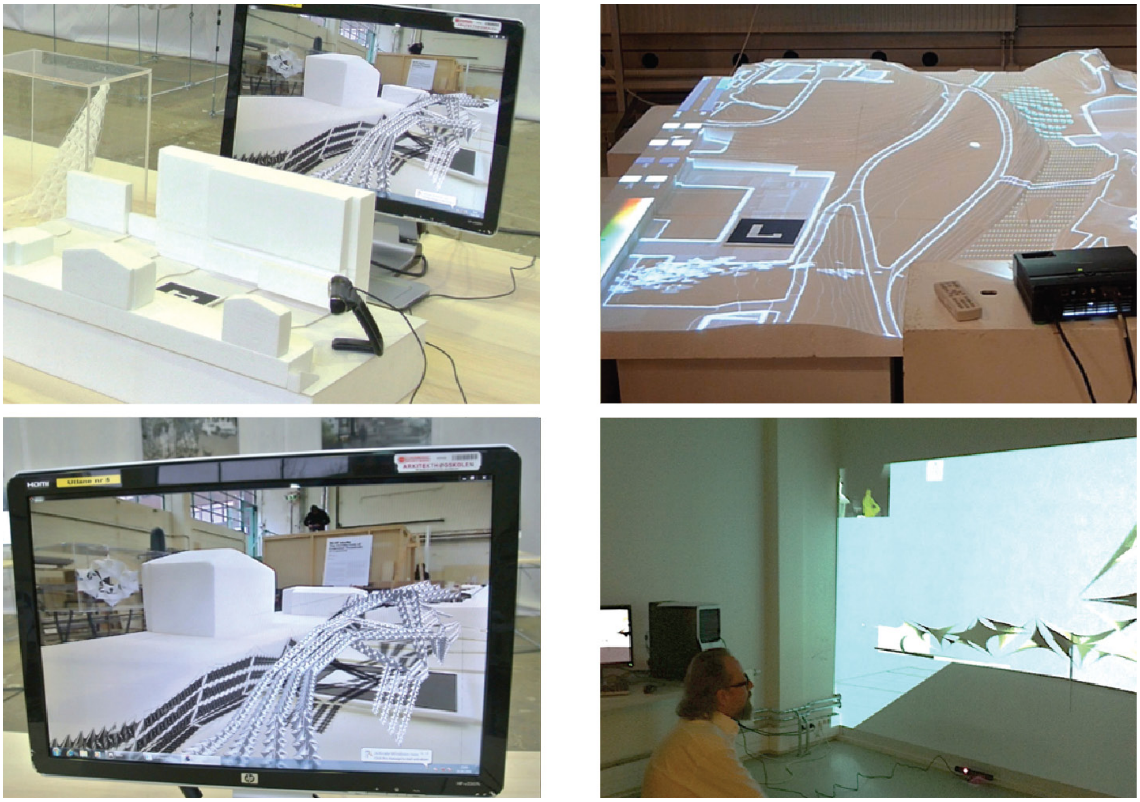

Fig. 2: Various AR and VR visualization set-ups developed and utilized in master-level studios and ACDL. These set-ups are all based on affordable and broadly available technologies. © Advanced Computational Design Laboratory, AHO – Oslo School of Architecture and Design.

stations intended for direct data-feed into computational models and analysis with real-time data, all of which serves to acquire a high level of climatic context-specificity for the designs. This procedure takes care of local variations and peak conditions that occur in specific sites not usually addressed by off-the-shelf software packages that operate on averages. This type of work extends the scope and inquiry from concept and design development and analysis to questions of workflow, workspace, tools and techniques, and the way architectural practice will need to be rethought in order to acquire the capacity for cutting-edge, performance-oriented design for a new and potentially vast market segment.

In the context of RCAT, various pilot projects have been constructed and analysed in order to deliver empirical data. Locally specific real-time data sets in the design process not only serve to get a much more nuanced understanding of the conditions that precede the design, and thus facilitate detailed analysis prior to implementation, but they can also continue to serve after construction in a manner not unlike post-occupation analysis, although extended beyond the interior or direct vicinity of a given architecture. To acquire this information, entire local environments need to be monitored with respect to context-specific, critical conditions and processes, and progressive and accumulative context transformation. The latter often leads to levels of complexity that require extensive data collection and analysis to enable comprehension.

The third design experiment combined the first, second and fourth lines of inquiry. Frequently, the data required for a particular design process may be already available, but needs to be located and often reformatted so as to drive the design process. The Seaside Second Home project focused on developing design strategies and computational methods for multiple-envelope, non-standard seaside homes for different locations on the west coast of Norway. [fig. 3] In relation to the overall pursuit of data-driven and informed non-standard architectures, the work constitutes a progressive case in advancing the concept. The specific local terrain articulation and the coastal wind and weather conditions served as environmental input into the design process and informed the articulation of the outer screen-type envelope.

The three sites for the project were strategically selected in order to obtain variation in two critical data sets: one pertaining to the terrain form and the other to the proximity of local weather stations. The specific terrain form of each location was derived from terrain-scans provided by the Norwegian authorities in the form of point clouds that that then required translation into a surface model. The three selected sites feature half-metre height line accuracy. From the point clouds a contour model was derived, the accuracy of which also served in the analysis of airflow across the site. The local weather stations delivered the site-specific wind conditions as data input into the generative design process. In this way, the design process was based on data sets that were retrieved from publicly accessible online databanks and converted into a format that can be fed into a generative computational design process.

The design consists of two envelopes: an outer permeable screen that shelters a transitional zone and an inner envelope of variable thickness. The articulation of the outer screen-like envelope primarily concerned the dissipation of horizontal wind loads and the modulation of thermal impact on the inner envelope. It also concerned the deceleration of airflow velocity from the exterior to the transitional space, so as to make it usable during more severe weather conditions. The screen and the outer surface of the inner envelope, constructed according to spatial requirements and environmental performance, articulate the transitional space. The interior is an open space articulated as an extension of the

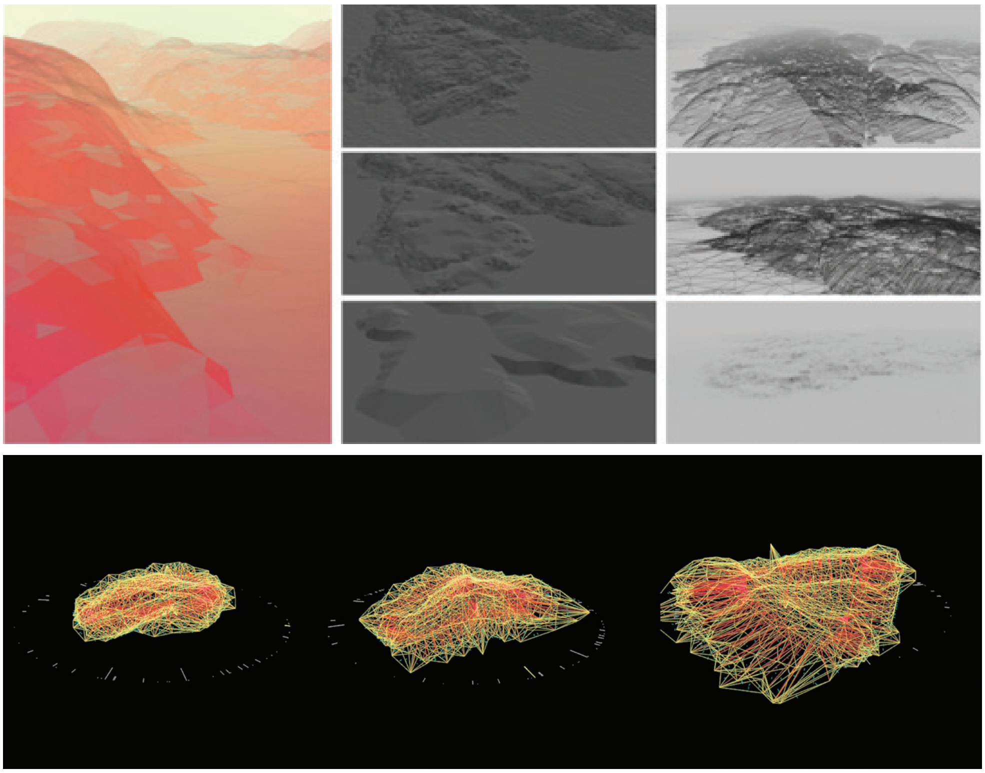

Fig. 3

Fig. 3: Data-driven design for three locally specific houses at the western coast of Norway. Terrain data derived from governmental terrain scans and form-generation based on coastal airflow conditions. Diploma project Joakim Hoen, 2012.

landscape and defined and constrained by sightlines. The variable thickness of the inner envelope emerges from the different criteria and algorithmic procedures pertaining to the outer and inner surface of the inner envelope. In methodological terms, the designs emerge as an outcome of a series of linked algorithmic procedures fed by data from publicly accessible sources, while employing the relation between environmental performance, programmatic intent, and material preferences as a set of design benchmarks that constrain the possible outcome.

The design of the three Seaside Houses was driven by the same type of integrated data sets, yet with a difference in degree as freestanding objects in surroundings not likely to change dramatically, resulting in variations and adaptation, but also a level of similarity. What characterises all of these design experiments is the pursuit of combined lines of inquiry and the co-development of custom configured design methods and tools, together with concepts and design approaches. Yet the goal is not to derive a universal, integrated toolset. On the contrary, the custom configuration of data-driven design methods and tools, or, in other words, the design of design processes, pertains, in our view, to the same capacity for adaptive expertise that architects acquire and utilise in the design of architectural schemes. The ability to custom configure and integrate case-specific methods and tools is of fundamental importance to the production of a desired outcome with increasingly complex performance demands.

Visualising Complex Data for Design

With the deployment of data-driven design comes the question of how to visualise complex data so as to enable comprehension on the part of the designer and ensure a tangible design process and workflow. This is obviously dependent on the complexity of information contained in each data set, the quantity and interdependence of data sets, and, in general, the complexity of the design problem. With the increase in this last aspect, it is reasonable to assume that the complexity of the former two will also increase. This, then, implies that the design problem needs to receive some attention.

One promising way of mapping complex systems and relations is based on Sevaldson's research into visual thinking and visual practice methods, in particular, a method he termed *GIGA-mapping*. Sevaldson described GIGA-maps as 'rich multi-layered design artefacts that integrate systems thinking with designing as a way of developing and internalising an understanding of a complex field'.[20] As a tool for visualising complex relations in an extensive manner, GIGA-maps can serve the purpose of redrawing system boundaries in a more detailed and expansive manner, or, likewise, provide the visualisation of multiple system boundaries in relation to different sets of criteria and/or different stakeholder configurations. In so doing, they enable the rethinking and redefining of design problems by unfolding an extensive set of interdependencies and relations that hitherto were not considered to this extent.

A second concern relates to the clarity and tangibility of visualisations that contain complex and dynamic data. Here, the typical object-focused visualisations deployed in architecture frequently fall short. Standard representation of spatial and dynamic data on a screen often proves difficult to comprehend. In this case, augmented and virtual reality tools can provide a more immersive spatial visualisation that can be shared among different collaborators during the design process. In the context of RCAT and ACDL, projects often involve experimentation with, and co-development of, AR and VR applications to support data-driven design processes. In the next section we will briefly describe two examples.

The *ARive Mobile BioTag* research project focused on the potential roles of architects and designers in the development of urban ecologies on an architectural scale. It operated from the correlation between the built, the farmed and the gardened in relation to the emergence and systemic complexity of natural systems. The proposed methodological approach combined Systems Oriented Design and *Giga-mapping* with advanced computational systems and visualisation, and purpose-made local weather station networks. Crowd mapping and augmented reality were used as the key technologies for registering, understanding, planning and increasing awareness, and for enabling the maintenance of urban habitats.

The implementation of augmented reality was made possible due to a decade of research on AR in architectural design directed by Sørensen at AHO.[21,22] Augmented reality serves this context primarily as a visualisation technology that can be described as a computer-assisted, real-time blending of digital, geo-localised, contextual information with the user-view of the actual physical surroundings. In short, AR enables the visualisation of data sets and simulations in context, not removed from, but in direct relation to, the environment. Although AR also encompasses aural information such as spatialised sound, current applications focus mostly on the visualisation of pre-modelled 3D structures, animated simulations, graphics, video and text. The actual simulation in most AR systems today is the relation between the digital structure or information and the physical surroundings in which AR is applied. Our objective is to develop systems where AR is a more integral part of the computational process.

The AR software entitled BioTag is intended to be proprietary and not reliant or based on open source code. The BioTag application includes real-time communication with databases on species and their interrelation, on-line access to official records and development plans, and full integration of the crowd mapping solution for geo-tagging and uploading registered information. In addition to utilising camera-recognition for recognising animal tracks, leaves and plant diseases, and retrieving information on these from databases and presenting them to the user, the system is also designed to utilise on-board GPS and gyro to position retrieved spatial information, such as proposed building volumes that can be viewed on the screen of the handheld device. In this way, the AR application enables access to sets of interrelated ecological information not normally readily available to architects, while visualising data in a tangible manner.

In the case of the ARive Østmarka National Park project – a cross between a Nature- Visitor Centre and a National Park Centre – this approach was further developed. Numerous commercial and freely distributed AR applications are available today, but none of these adequately offers users the possibility of easy adaptation to their own needs. Often, programming skills are required, or the use of pre-created software with little or no real-time control. However, architects and designers need to be able to implement their own models with the possibility of manipulating these in real-time.

An integral part of the project was therefore to further develop major parts of the AR solution from the ARive mobile BioTag project to the level of a fully functioning application for Android OS. The resulting software was divided into two parts: (i) a design and process tool for architects and designers, and (ii) a dedicated application constituting the information retrieval/presenting and user interface for the distributed National Park Visitor Centre. In addition, the weather station network described above was further developed so as to feed real-time data to the AR system. [fig. 4] Prerequisites for both were ease of use, robustness, minimal response time, stable and high frame-rate, and high quality rendering. In addition, ARive Mobile enabled the import of models with materials, custom lighting and real-time shadows, tools for airflow and sunlight analysis. This, then, allows architects and designers to use AR in various ways, including in the design process for the evaluation of design iterations in context, as an analytical tool to visualise data, for defining and integrating external environmental data and presenting projects, and for defining the environmental conditions of the specific local setting.

The second iteration of ARive is as a working prototype for use in the park itself, with the software and framework constituting the visitor centre. Instead of adhering to a traditional procedure and strategy of designing, the centre could be incrementally developed as a distributed system of autonomous physical and virtual nodes connected as an integrated unity that together constitutes a National Park Visitor Centre, independent of traditional built structures. The benefits are the geographic distribution of processes, resource-sharing independent of large central resources, fault tolerance and scalability.

The intermittent realisations that arise from this line of inquiry, which concerns the visualisation of complex conditions and processes for designers and for use in the design process, are threefold: (i) AR and VR visualisation is able to provide an immersive environment in which design can focus on performative aspects based on interactions between architecture and the environment (see, for instance, the auxiliary architectural research); (ii) such visualisations can underlie and facilitate interdisciplinary research and design efforts by making conditions tangible and comprehensible that are not normally within the knowledge domain of architects, and (iii) the user can be involved either in the design process, or, alternatively, have a visually extended information source that transcends the physical object and its interaction with the environment.

Conclusion and Outlook on Further Developments

This paper has discussed various stages of developing data-driven computational design processes en route to performance-oriented, intensely local architectures and tectonics. Each of the examples discussed displays a different range of integrated methods. What emerges from the various above-mentioned projects is an understanding that the emphasis of design is gradually encompassing a range of specific local conditions and processes across spatial and time scales. These conditions need to be defined on a case-by-case basis in relation to the specific aspects of the design brief and setting, with each case being extensively mapped out in its complex relations. Giga-mapping may serve as one method for doing so.

This approach also involves a number of dynamic processes, each with its own duration, velocity and timeline. What this points to is the need for data-driven generative processes to also be configured case-specifically. For this to be possible it is necessary to consider the specifically relevant sets of data, their interrelations, the process setup, the definition and delimitation of the specific search space, criteria and methods for analysis and evaluation, aspects of comprehensibility and thus visualisation, and, ultimately, the workflow and workspace. These factors, in turn, indicate the need to reconsider the training of designers so that they are able to work in this manner. For this reason, lines of inquiry are specifically defined and combined for each design problem and local setting.

While integration into a unified toolset may seem tempting, different modes and combinations of integrated methods and tools need to be pursued. And while generalisation is always to some extent necessary, it may soon get in the way of catering for a local specificity of conditions that are not only different in degree but also in kind. This relates in obvious ways to the level of complexity an architect

Fig. 4: Custom-made weather station and the ARive Østmarka National Park Project application which utilises and visualises life data transmitted by the weather stations and other sources. Diploma project Joachim Svela, 2013.

wishes to encompass and address in the design work. Therefore, it seems useful to foreground the capacity for adaptive expertise not only in relation to architectural design in general but, more specifically, to the integration of related objectives, concepts and methods vis-à-vis data-driven generative design.

Obviously, prescriptive, finite approaches run counter to the intent of deriving an intensely locally specific performative architecture, unless the objective is to arrive at yet another style or 'ism' in architecture. If, however, the intent were to engender the design of a broad range of architecture and environmental interactions, it would seem clear that no single architectural expression or style could result from this. What is critical at this stage is to acknowledge the associated conceptual challenges and potentials in relation to defining an intensely local architecture based on locally specific data sets. One immense challenge is generated by conditions involving complex interactions that are mutually inhibiting or accelerating, that spiral upwards in scale, that exceed critical thresholds, and, as a result, lead to dramatic changes. This should alert us to the fact that the results of data-driven generative design processes should be evaluated with a necessary degree of caution.

At this stage we have (i) studied the performative capacity of materials and material systems in interaction with specific environmental conditions that were informed by, and checked against, material experiments; (ii) explored architectural designs derived from their interaction with environmental condition inputs, whether finite or enduring, and, wherever possible, tested these in full-scale constructions; (iii) commenced the conceptualisation of niche creation and design for biodiversity in architecture, an approach that will require more complex data-driven processes, and (iv) commenced utilising AR and VR tools during the design process as a way of making complex aspects and interactions more comprehensible, and enabling a more spatial experience of these interactions.

These different elements within our research seem compatible and integrable if a specific design problem requires this integration. Generally, however, it is of vital importance to map, define and integrate conceptual and methodological objectives for a given design problem or project in its own right. To instil this capacity for tapping into the considerable potential of using data-driven computational design processes is our aim.

Notes

1. Kenneth Frampton, 'Towards a Critical Regionalism: Six Points for an Architecture of Resistance', in *The Anti-Aesthetic: Essays on Postmodern Culture*, ed. by H. Foster (Port Townsen: Bay Press, 1983), p. 21.
2. Ibid.
3. Ibid. p. 17.
4. For a detailed discussion see Michael Hensel, *Performance-Oriented Architecture – Rethinking Architectural Design and the Built Environment* (London: AD Wiley, 2013).
5. Ibid.
6. ANT – Actor Network Theory as formulated by Michel Callon, Bruno Latour, Johan Law, et al.
7. In 2003-04 the Centre Pompidou in Paris mounted an exhibition titled *Non-standard Architectures*. It foregrounded the capacity of computer-aided design in the production and industrialisation of architecture with the aim of showcasing 'the generalisation of singularity, within a new order: the non-standard'. This was demonstrated by built and unbuilt projects by some of the key proponents of digital methods and techniques since the early 1990s, such as Asymptote, deCOI, Greg Lynn FORM, KOL/MAC Studio, NOX, Objectile, Kas Oosterhuis, R&Sie and UN Studio. In 2014, the authors of this paper curated an exhibition entitled *Informed Non-Standard*, which examined the integration of both computational design approaches and tools. The aim was to synthesise form, performance,

use and making, and, in an increasing number of cases, the re-emerging role of local, context-specific conditions that can underlie and inform these integrated computational design approaches. The exhibition took place from 28 April to 22 May at Galleri AHO in Oslo, Norway.

8. Scarcity and Creativity Studio <www.scls.no> [accessed 03 July 2014]
9. For a detailed elaboration of the role of the spatial and material organisation of ground and envelopes as vital performative elements, see Michael Hensel and Jeffrey P. Turko, *Grounds and Envelopes*: *Reshaping Architecture and the Built Environment* (London: Routledge, 2015).
10. Kenneth Frampton, *Studies in Tectonic Culture*: *The Poetics of Construction in Nineteenth and Twentieth Century Architecture* (Cambridge MA: MIT Press, 1996), p. 5.
11. Ibid. p. 5.
12. Ibid. p. 6.
13. This may, for instance, entail considerations as to how locally specific practices such as 'the right to roam' (in Scandinavia the 'all man's right') – a series of customary practices that govern public access to uncultivated and/or privately owned land – can underpin approaches to settlement organisation and ground articulation. Such an approach can help to embed otherwise overly generalised settlement patterns and building types into locally specific settings and practices.
14. For a discussion of architecture and environment interaction, both in terms of design generation and intended output, see Michael Hensel 'Material Systems and Environmental Feedback Dynamics', in *Emergent Technologies and Design: A Biological Paradigm for Architecture* (London: Routledge, 2010) pp. 63-81.
15. This is frequently done in the Scarcity and Creativity Studio (www.scls.no) at the Oslo School of Architecture and Design.
16. For a detailed account of related experiments see *Morpho-Ecologies,* ed. by Michael Hensel and Achim Menges (London: AA Publications, 2006), and *Form Follows Performance*: *Zur Wechselwirkung von Material, Struktur, Umwelt*, ed. by Michael Hensel and Achim Menges, Arch+188 (2008).
17. Michael Hensel 'Confronting the Crisis of Architectural Education', in *Nordic Journal of Architecture*, 1, 2 (2012), pp. 85-9.
18. Defne Sunguroğlu Hensel and Guillem Baraut Bover, 'Nested Catenaries', in *Journal of the International Association for Shell and Spatial Structures*, 54,1 (2013), pp. 39-55.
19. For a detailed discussion see Michael Hensel, *Performance-Oriented Architecture*: *Rethinking Architectural Design and the Built Environment* (London: AD Wiley, 2013).
20. Birger Sevaldson, 'GIGA-Mapping: Visualization for Complexity and Systems Thinking in Design', Nordic Design Research Conferences, Helsinki, 2011 < http://ocs.sfu.ca/nordes/index. php/nordes/2011/paper/view/409/256 [accessed 02 October 2011]
21. Søren S. Sørensen, 'The Development of Augmented Reality as a Tool in Architectural and Urban Design', in *Nordic Journal of Architectural Research*, Vol. 19, No. 4 (Blindern: SINTEF Academic Press, 2006), pp. 25-32.
22. Commencing from the visualisation of radiation fields in nuclear reactors, AHO has been part of a multi-disciplinary research effort with the Institute of Energy Technology, IFE, Norway, and the University of Kyoto, Japan. Through this collaboration, new AR systems were developed with a main emphasis on full-scale visualisation of architectural structures on site.
23. Søren S. Sørensen, 'Augmented Reality for Improved Communication of Construction and Maintenance Plans in Nuclear Power Plants', in *Progress of Nuclear Safety for Symbiosis and Sustainability, Advanced Digital Instrumentation in Control and Information Systems for Nuclear Power Plants*, ed. by Hidekazu Yoshikawa and Zhijian Zhang, (Osaka: Springer, 2014), pp. 269-74.

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Footprint is a peer-reviewed journal presenting academic research in the field of architecture theory. The journal addresses questions regarding architecture and the urban. Architecture is the point of departure and the core interest of the journal. From this perspective, the journal encourages the study of architecture and the urban environment as a means of comprehending culture and society, and as a tool for relating them to shifting ideological doctrines and philosophical ideas. The journal promotes the creation and development – or revision - of conceptual frameworks and methods of inquiry. The journal is engaged in creating a body of critical and reflexive texts with a breadth and depth of thought which would enrich the architecture discipline and produce new knowledge, conceptual methodologies and original understandings.

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