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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 inter-action 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 envi-ronments through real-time interactions between natural or artificial environments and users. The assumption is that data-driven design should estab-lish 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 mate-rialisation but also about the operation and use of buildings or other artefacts and their components. Data becomes a single source for conceptualisa-tion, 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 repre-sentation 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 architec-tural 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 fabrica-tion 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.