

The Architecture Machine Revisited

Experiments exploring computational design-
and-build strategies based on participation

Jeroen van Ameijde

Architectural Association (AA) School of Architecture

Abstract

This article summarises a series of experiments at the Architectural Association between 2011 and 2017, which explore the intellectual notion of 'the architecture machine' as introduced by Nicholas Negroponte and the Architecture Machine Group at MIT in 1967. The group explored automated computational processes that could assist the process of generating architectural solutions by incorporating much greater levels of complexity at both large and small scales. A central idea to the mission of the Architecture Machine Group was to enable the future inhabitants to participate in the decision-making process on the spatial configurations. The group aimed to define architecture as a spatial system that could directly correlate with human social activities through the application of new computer technologies.

Our research presented here focuses on technologies and workflows that trace and translate human activities into architectural structures in order to continue the research agenda set out by Negroponte and others in the 1970s. The research work discusses new scenarios for the creation of architectural structures, using mobile and low-cost fabrication devices, and generative design algorithms driven by sensory technologies. The research question focuses on how architects may script individual and unique processes for generating structures using rule-sets that organise materiality and spatial relationships in order to achieve a user-driven outcome.

Our explorations follow a renewed interest in the paradigm where the architect is a 'process designer', aiming to generate emergent outcomes where the inherent complexity of the project is generated towards specific performance criteria related to human activities and inhabitation.

Keywords

on-site sensing and construction technologies; participatory design; computational design; emergent design; custom robotic devices; digital construction

Introduction

The Architecture Machine group at MIT was founded in 1967 as a ‘workshop of ideas for the development of human-computer interfaces’ (Orazi, 2015), headed by a recent graduate, Nicholas Negroponte. It eventually grew to become the MIT MediaLab we know today with wide-ranging research into future applications of new technologies. When the Architecture Machine Group was founded, computers were still very rare, bulky, and expensive. Yet, they attracted the interest of several architects and scholars who were fascinated by mathematical analyses, diagrams, and the idea of designing with new and less arbitrary logical approaches (Orazi, 2015). Negroponte and his collaborator Leon Groisser worked on information systems, computer graphics, and computing protocols that improved the interface between the architect and the machine, and published the book *The Architecture Machine* in 1970. Negroponte’s notion of the ‘machine’ means an ‘abstract’ machine, capable of generating design solutions from information inputs about the end user of an architectural project. It was important for him to define this effort not as a fully automated, autonomous process but rather as a partnership in collaboration with the human designer:

“This discussion is not about machines that necessarily can do architecture; it is a preface to machines that can learn about architecture and perhaps even learn about learning about architecture. Let us call such machines architecture machines; the partnership of an architect with such a device is a dialogue between two intelligent systems—the man and the machine—which are capable of producing an evolutionary system” (Negroponte, 1969).”

The book set out a utopian vision that combines humanism with futurism and speculates on the possibility for combined man-machine processes to accurately and creatively translate each client’s requirements and desires into detailed architectural design free of the architect’s self-interests. The outcomes of each process would never be standardised, as the computational tools would allow the integration of the character of ‘a designer of another temperament or of another culture’ (Negroponte, 1970). It also expands radically upon the perception of computer systems at the time, which were starting to be used in architectural practice for drafting and problem-solving tasks, a tendency which was believed to bring the danger of an ‘industrialisation’ of the profession.

“Most computer-aided design studies are irrelevant inasmuch as they only present more fashionable and faster (though rarely cheaper) ways of doing what designers already do. And, since what designers already do does not seem to work, we’ will get inbred modus operandi that could make bad architecture even more prolific” (Negroponte, 1969).“

The implementation of the agenda of the group may have been too ambitious for its time. There were few viable outcomes due to the limitations in computer technologies. Yet its agenda has been highly influential and the focus of renewed interest in recent years. The most well-known project among academics and the art world is the installation entitled ‘Seek’, shown during the ‘Software’ exhibition at the Jewish Museum in New York in 1970 (Fig. 1).

The installation consisted of a large Plexiglass enclosure containing a three-dimensional landscape of small cubes, which could be analysed using a camera and manipulated by a robotic arm. A computer system processed the images from the camera and activated the robotic arm, thus creating a closed feedback loop system between the environment and the computational module. Inside the plexiglass case was also a number of gerbils, small mouse-like animals whose kangaroo-like movements would disrupt the cubes. The provocative research question behind the installation was that there was no fixed blueprint of the desired three-dimensional arrangement of cubes, but that the system was calibrated to analyse and amplify

the gerbils' interventions. The ideal 'final' configuration of the cubes would emerge over time, out of the interaction between the inhabitants and their architectural environment.

The project was technically considered a failure, as there was no stable outcome achieved by the system.

"Unknown to SEEK, the little animals were continually bumping into blocks, disrupting constructions and toppling towers. The result was a continually changing mismatch between three-dimensional reality and the model residing in the core memory of the computer. (...) SEEK did show inklings of responsive behaviour because its reactions were based on probabilities and it was programmed to either correct or amplify (not both) the dislocations caused by the gerbils" (Rowe, 1972).

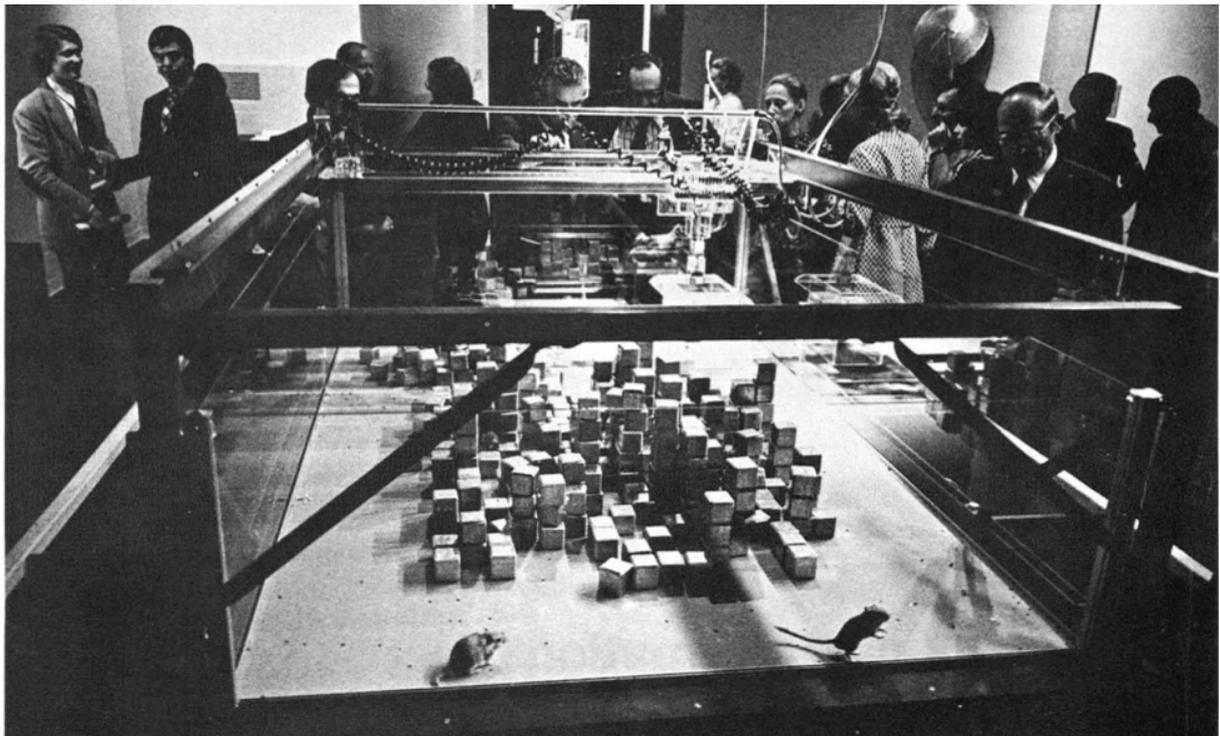


FIGURE 1 Seek' installation by Nicholas Negroponte and The Architecture Machine Group, 1970.

The installation, however, made an important contribution to the debate about new technologies, reaching audiences beyond the narrow field of scientific research. It demonstrated the ambition to 'bring urban design back the ordinary man', allowing every citizen to be involved in the complex negotiations around urban problems through the mediation by an accessible and fair computational system. Negroponte's larger aim was to democratise and localise the control over the design of the built environment, developing 'humanistic' machines that could respond to user requirements, analyse user behaviour, and even anticipate possible future problems and solutions. The 'Seek' installation was intended as a provocation and a starting point for a range of research projects investigating its translation into practice, as the team behind it were well aware of the complexities of operating within human societies and with architectural design processes in particular. Within five years, Negroponte published a second book entitled 'Soft Architecture Machines', which acknowledged that pursuing a 'machine intelligence' was too ambitious for the time and the interim focus should be on 'design amplifiers': informed machines that allow end users to participate in the design process.

Other architects who were contemporaries of Negroponte worked on similar research projects, including Yona Friedman, who, in addition to his 'Ville Spatiale' proposals, developed a strategy for a machine that would translate the personal preferences of an inhabitant into visualisation of his dwelling to engage neighbours and builders (Friedman, 1971). Friedman, as well as other contemporaries including Christopher Alexander, John Habraken, Ralph Erskine, and Giancarlo De Carlo, developed work around the principle of participation and received both praise and condemnation from those who felt threatened by the proposition of limiting the traditional role of the architect as the sole author of their work.

There is a renewed interest in our current time in the 'philosophy of participation', in part due to a resurgence of humanist priorities within the architectural discipline, exemplified in the attention given to the projects by Alejandro Aravena and his company ELEMENTAL. Aravena's half-finished homes, which could be completed by residents, addressed the high cost of home ownership as well as people's desire to individualise their home's layout and expression. The team of architects and engineers devised a system of rules, manuals, and workshops to guide the processes of participation, similar to how the rules within 'the architecture machine' of the 'Seek' project aimed to guide the outcomes to stay within a bandwidth of desirable possibilities. The role of the architect is not to micro-manage each formal solution but rather to define a set of performance criteria to which each solution must adhere. These performance criteria are prioritised to satisfy safety concerns and to deal with mediating potential conflict between neighbours, while aiming to provide freedom for flexible adaptation by the users.

Contemporary Technological Developments

A range of technological developments that are changing the design and construction industry in our current time allows us to rethink how the agenda of the Architecture Machine Group and its contemporaries can be revisited. The philosophy of participation can now be applied to a new generation of computational infrastructures, including increasingly accessible design and production software packages connected to computer numerically controlled or robotic fabrication. The term 'robotic' in this context could refer to mobile robotic arms similar to those used in the car manufacturing industry, as well as to a whole range of other hardware and communication tools that can be merged within segments of the more traditional means of construction. Some are already in use in factories and on construction sites today. These devices and protocols, ranging from 3D scanning to laser guided measuring and positioning equipment, are not aimed at fully automated construction but rather at a much more precise man-machine collaboration.

As robotic fabrication and assembly devices are being introduced into the construction industry, it becomes possible to rethink the entire process of how architectural projects are materialised. Construction processes no longer rely on inefficient communication protocols relating to manual workers and manual tools but can be directly informed by digital 3D models coordinated by a design team. This could increase quality, reduce errors and cost, and potentially reduce construction periods. It could also be used to deliver projects of increased complexity, due to the ability of these new construction systems to perform large amounts of operations at high precision. As robotic devices are becoming mobile and capable of working collaboratively, this paradigm can be applied to the scale of the building site instead of being limited to the working envelope of a single device.

The enhanced communication between design software and construction technologies signifies a fundamental shift in the possibilities of design. Projects can potentially be conceived and built with a much higher resolution of material properties and with a high degree of internal differentiation, rather than repetition. Instead of applying robotic tools to the production of sculptural or decorative complex

geometries, a much more radical opportunity presents itself: the incorporation of much higher degrees of *functional* complexity into the process outcomes.

The architectural design, and therefore the design process as well, could incorporate complex properties of a building's performance within its environment through detailed simulations and real-world data gathered through sensors, measurement, and mapping processes. Performance could be understood within the context of physical environmental and climatic conditions such as sunlight, wind, temperature and noise. This is indeed one of the great potentials of digital design processes, to deliver increased building quality, efficient and high-quality spaces designed around human comfort. But performance analysis can also be applied to how buildings perform within their socio-economic context, stimulating interaction and collaboration through the careful distribution of human circulation and inhabitation. Within the practice of planning the layouts of large office buildings for instance, it is already commonplace to consider the interplay between the comfort, psychology, and productivity of employees and the arrangement of furniture can directly influence the economic success of a company. The layout of shelves and the product placement in supermarkets is designed to increase sales of the most profitable items, considering the visual navigation and behavioural psychology of the customers. Through increasingly precise monitoring systems that build up large data-sets of statistical analysis of human activities, the design processes that optimise spatial layouts are increasingly being automated, informed by semi-intelligent processes such as machine learning.

While commercial applications might push the rapid development of data-driven design, academics and practitioners have an opportunity and, arguably, an obligation to critically examine the consequences, be they negative or positive, of these new processes. Generative design processes can be used to observe human behaviour and define the properties and organisation of spaces to stimulate desirable activities in the most effective way. These processes could be used in the design stage of a project, as well as for the continuous management or adaptation of the project throughout its life. Occupied buildings could be in continuous communication with a digital version of itself, which, in addition to being a centralised information model of all of its physical parts (such as in most current BIM applications), also evaluates the use of its spaces through the monitoring of human activities that take place.

This integration of sensing and analysis processes within the design, construction, and operation of buildings raises profound questions about the ethics and policies around the translation of user data into design decisions or building-use protocols. Similar to the recent public debate about social media platforms being used to steer consumer behaviour or to influence democratic processes, building control systems might have to be reconciled with the ethical standards of our current societies. It is up to the architectural profession to debate and explore the opportunities from these new technological possibilities, instead of letting them be advanced by parties only interested in the commodification of user data for profit. Architects and planners could speculate on how they can calibrate 'machinic' built environments towards physical and psychological comfort, creating private and public spaces that promote quality of life and societal progress.

Data-Driven Design at the Urban Scale

Several strands of research into the underlying principles of human decision-making within urban environments can be found in the 'smart city' area. It has developed into a significant field engaging academics and professionals around the world. The idea of the 'Smart City' was first introduced in the 1990s. But it has only recently attracted higher profile projects and attention, resulting in the execution of multiple projects and policies in cities around the world today. The goal of a 'Smart City' is to use technology to create

economic, social and environmental improvements. This challenge is not only related to design and planning issues, but also aimed at the economic and political frameworks that guide urban development. 'Smart City' projects attempt to understand the urban ecologies – the invisible networks of human activities that drive the materialisation of the city.

The sociologist Jennifer Gabrys has written about the “new wave of smart-city projects that deploy sensor-based ubiquitous computing across urban infrastructures and mobile devices” (Gabrys, 2014). She notes the potentially positive ambitions of these projects to improve sustainability but also warns of the potential dangers of monitoring and managing data on citizens. She references the French philosopher Michel Foucault (1926 – 1984) who has written extensively about mechanisms of power and control exercised by the state, and how its manifestations in the structures of buildings and the city can be understood as a 'biopolitical machine'. Gabrys argues that smart-city design processes should focus on the performance of urban environments as demonstrated through the behaviour of people within them rather than collecting data on citizens and populations. The sensitive subject of monitoring human activity should be approached with the necessary safeguards to ensure privacy and data protection of individuals and allow for open-endedness towards behavioural patterns and demographics.

Methodology: Generative Design

The practice of generative design is well established within industrial design and engineering disciplines and can be defined as using a computational design process aimed at creating the best possible solution against specific performance criteria. It can be considered a sub-category of the larger field of 'parametric design', the terminology that is sometimes misunderstood or falsely advocated as being necessarily associated with an architectural language of curvilinear form. It detracts from the much more systemic improvements that these methodologies can bring to the field of architecture. The 'parametric design' considers certain parameters or relational modelling techniques during a design process. The practice of 'generative design' requires the definition of clear goals for the design solution, making it particularly suited for data-driven design in evaluating potential design options against detailed contextual information.

The potential role of generative design processes was identified early on by Mitchell and McCullough in 1991. They contemplated the implications of computational processes in order to address a complexity of parameters and interactions, much greater than by human cognitive processes alone. (Mitchell & McCullough, 1991). Like Negroponte, rather promoting 'automated design procedures', they emphasised the central role of the designer's intellectual capacity and critical judgement in relation to the employment of algorithms, the input of data parameters, and the definition of the evaluation criteria. Generative design in this context operates on the underlying relationships rather than the formal characteristics of the built environment. As Lima and Kós write, 'this form of algorithmic or parametric modelling transcends the understanding of the computational paradigm as a mere promoter of complex forms, and contributes to processes capable of forming models that contemplate several parameters involved in the functional, environmental and of the cities and the buildings they contain' (Lima, 2014).

In our research, we interpret the practice of generative design as a methodology with a clear logic and consistent step-by-step translation of design information over time. This allows for the design process to 'generate' traceable solutions that can be evaluated against the performance criteria that informed the design process in the first place. This approach using rule-sets allows us to generate site-specific outcomes within the limitations of a particular context and to take full advantage of and contribute to environmental, programmatic, and connectivity characteristics of the surroundings.

Project 1: Point-Cloud

The first project testing rule-based design methods and in-situ digital fabrication and construction technologies was a small experimental structure situated in the forest of the Dorset campus of the Architectural Association.

The project used a custom-built cable robot device, designed to act as a 3D location point indication device on site. It functioned through a CNC protocol to manipulate the length of three wires on spindles attached to stepper motors. The wires were installed in a site by attaching three pulleys to existing trees or buildings around an empty area. This system is adaptable and scalable: a wide range of sites can be turned into a CNC working envelope. The CNC machine was connected to a laptop with the widely used G-Code control software Mach 3, allowing the wire pointer to move to a specific coordinate in 3D space similar to how the cutting head is moved around on a three-axis CNC milling machine (Fig. 2).

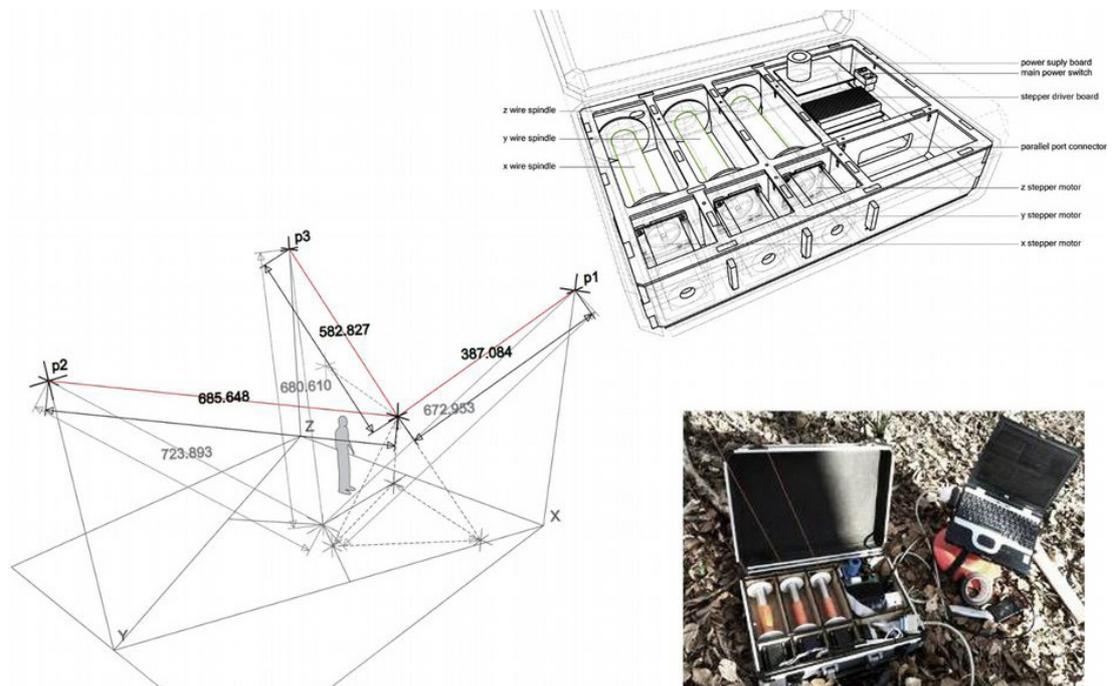


FIGURE 2 CNC cable robot used as point indication device.

The project explored a digital work-flow which translated 3D scanned data of people movements and densities towards a corresponding cellular structure to be built on site. The movement data was collected by using a KINECT 3D camera to gather point cloud data of human bodies within the site for 10 minutes. A semi-automated design work flow was set up to handle the translation of the point cloud information from the 3D scans to the specific geometry to be built using cell-packing and tessellation algorithms (Fig. 3). The design method was calibrated to translate higher intensities of movement into increased densities within the structure, visualising previously invisible qualities on site and guiding subsequent visitor movements along specific paths.

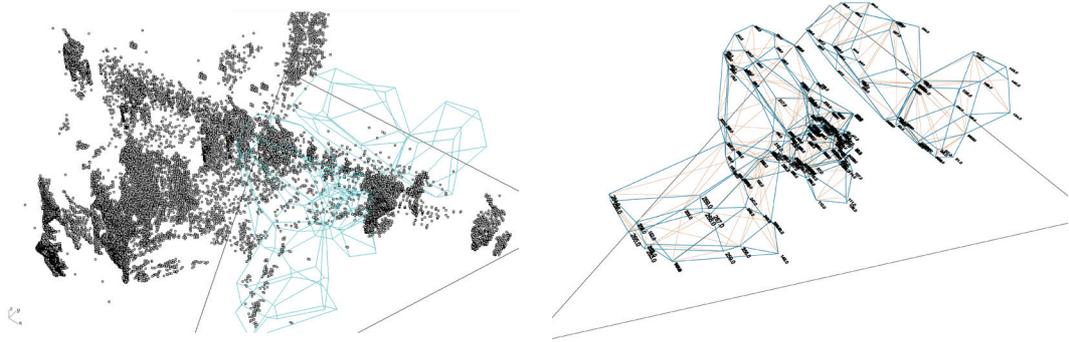


FIGURE 3 3D scans of movements of people through the site, translated into a triangulated structure through a generative design process.

The construction system was deliberately designed as part of a human-machine collaboration, envisioning a scenario in which the device is only used for its most important task: the translation of detailed construction information from a digital model containing three-dimensional point locations onto a building site. The human collaborators did those tasks that they can do better than machines, such as the manual handling and connecting of building elements (Fig. 4).



1



2

FIGURE 4 Human collaborators installing timber elements guided by the cable robot pointer, resulting in a variable density triangulated structure.

The 'Point-Cloud' project demonstrated the potential of a generative design process based on site-specific data. However, the design properties of the physical structure did not change or contribute additional functionalities regarding the movement in the site. Successive projects have been set up to incorporate this ambition, not just passively responding to the data gathered on site, but aiming to introduce improvements to the found conditions.

Project 2: Emergent Constructions

The second project in our research consisted of a medium-size architectural pavilion with a temporary cluster of spaces and seating elements for visitors to a large shopping mall in Kuwait. By recording the movement of people using digital cameras through a central atrium space, the prevailing pattern of visitor flows was mapped in relation to the entrances and attraction points within the mall. Data regarding user density and sight lines between the pavilion location and the surrounding amenities were translated into the design of a pavilion that would intervene in the existing site. This would produce an attractor point in an area that was identified as low in activity, intervene in the general paths of circulation, and create a louvre effect between the internal spaces and the context to offer varying degrees of privacy for the people inside (Fig. 5).

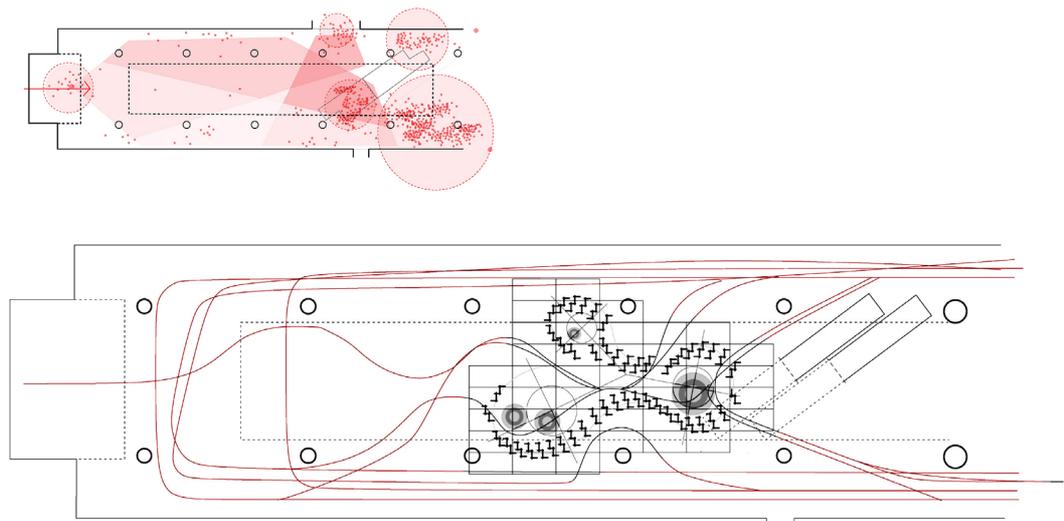


FIGURE 5 Louvre walls enclosures generated in relation to visitor intensities and sight lines.

The resulting qualities of space cover a range of social interactivity scenarios, including private space for a single occupant and larger group spaces for dynamic social interaction and play. The programmatic possibilities were further enhanced through the incorporation of furniture elements such as benches and stools. The generative design and construction exercise resulted in a pavilion that manifested itself as a field condition, distributing a large amount of self-similar elements with varying properties and relationships within the circulation space of the mall to intensify and enrich its spatial and programmatic possibilities (Fig. 6).

The pavilion as a field of elements with different heights, density, and functions created a varied architectural landscape that incorporated specific intentions for stimulating social interaction. The multiple possibilities of use and interpretation, however, allowed the users to create their own social patterns and interactions, and explore unforeseen modes of engagement with the design at the many in-between spaces of the pavilion. The role of the architecture was conceived as creating a stimulating environment with a strategic purpose and agenda without being prescriptive or inflexible but instead creating an open-ended system for appropriation by the users of the mall.

The principle of feedback between architecture and users is further explored in the subsequent projects. This research follows specific strategies for user-based design as described by Nicholas Negroponte and the Architecture Machine Group in 1970.



FIGURE 6 Pavilion spaces designed to mediate between privacy and social interaction.

Project 3: Emergent Field

The project entitled 'Emergent Field' explored a generative, rule-based design strategy that monitored people's movement through a specific forest site and materialised this as a field of timber poles placed vertically within the terrain. This material system facilitates the ease of construction and the compatibility of the geometries with the CNC controlled device that we used, the cable robot device as introduced and described previously in Project 1. The vertical poles allow the wires of the cable robot to be moved among the elements. If the movements of the pointer were choreographed to drop down vertically each time, it would indicate a new location point. This characteristic enables the system to build additional pieces inside areas that had already been populated with the poles.

The project explored a process where the final formation was not known at the beginning of the construction process but was allowed to emerge throughout a series of iterations consisting of movement tracking, generative design translation, and construction. A digital camera facing vertically downwards to the construction area took snapshots, over a period of time, of the locations of people. A simple processing software selects the areas of red colour as all participants in the experiment wore red head coverings. The recorded site occupation density patterns were automatically translated into geometrical patterns for the timber pole formations using a generative design process based on simple rules (Figs 7). The movements were recorded during breaks between the building activities when people were asked to freely pass through, explore, or inhabit the forest site.

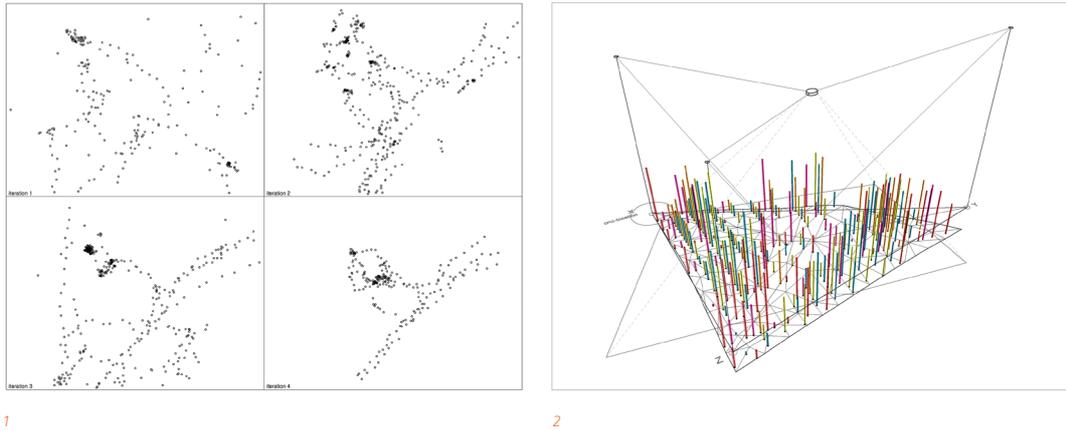


FIGURE 7 Density maps and timber pole patterns generated by web-cam monitoring of people, showing the iterative refinement and densification around pathways and hangout spaces.

Each iteration resulted in a construction pattern that added additional density in areas which the people hadn't occupied, gradually articulating the edges around movement pathways and inhabitation spaces with rows of vertical poles. The initial layers of elements within the site were placed with a generous spacing, to allow users to move in between the poles that were placed, still suggesting adjustments to the patterns that was gradually emerging. The gradual refinement and articulation of circulation and inhabitation areas occurred within both the digital design model and the physical space, thus allowing the final design to be informed through the active negotiation between material and users around the real experience of the installation in the site (Fig. 7).

The outcomes of the project might seem abstract and show a significant reduction in the amount of functionality compared to the previous project, yet the iterative design and build process signifies a radical improvement in the process of design conception and data management. Instead of 'freezing' a data-set containing site information, the relevant parameters continued to be monitored throughout the construction process, allowing the building design to keep adjusting to new information from the site caused by the intervention being placed. The feedback loop between a structure on site and the resulting user activities around it, allows for a design process to continuously monitor the performance of its output and learn how to make improvements within it.



FIGURE 8 Construction and final installation of the field of elements on site, using a web-cam suspended from the trees and a cable robot pointer device.



FIGURE 9 Construction and final installation of the field of elements on site, using a web-cam suspended from the trees and a cable robot pointer device.

Project 4: Public Space Furniture

The fourth project built on a series of experiments inspired by Negroponte's 'Architecture Machine'. It was executed with help of several students and used the terrace of the Architectural Association as a testing ground. A web-cam pointing towards the space recorded people inhabiting the terrace, documenting their position, duration of stay, and distance to others (Fig. 10). A set of computational rules was then applied on to these maps, instructing the human assistants in the project to place furniture elements around the site. Specific rules and policies were explored to award or discourage certain behaviours, for instance, placing furniture in positions that would encourage social interaction between people or instead create separation between people. The experiments produced emergent outcomes, with an architectural structure that was grown over time without predetermined design. Users interacted with the structure through sitting, leaning, placing coffee cups, and so forth, and generally stayed longer and engaged in more different activities than they would have normally done within this site.

An initial furniture system was implemented using plastic crates, which led to increased social interaction within the site and greater engagement of the visitors with the experiment. In the second phase, a custom CNC-fabricated furniture system was deployed that allowed for cantilevering elements and incorporated open and closed panels to block sight lines and create privacy (Fig. 11).



FIGURE 10 Snapshots of people monitoring as seen through the web cam and as analysed by blob-tracking algorithms.

FIGURE 11 Sequence of iterative furniture placements and usage based on people monitoring and specific response policies.

The experiments conducted as part of this project added yet another level of complexity to the body of research, testing specific reactionary social policies as part of an iterative scan and build process that incorporates feedback loops. The large number of variables in the experiments makes it difficult to evaluate with precision which rule-sets or furniture configurations are more effective than others. The project was mainly intended as a proof of concept that this type of process could generate concrete results.

Project 5: Data-Space

The fifth and most recent project in the series is by no means the final development as it was intended to offer an even higher degree of speculation and to open up additional avenues of contemplation about continuous monitoring and feedback systems embedded within the built environment. Entitled 'Data-Space', it was developed by the author in collaboration with the faculty and students specialised in interaction design from the ArtEZ University of the Arts in Arnhem, The Netherlands, as well as with collaborators from within the Architectural Association. The project explored the use of a field of nodes that each incorporate a sensor and LED lighting, monitoring, and communicating with people within the site in a distributed and scalable way, as opposed to the previous projects which were limited by the use of a digital camera. The nodes were arranged in a gridded field and suspended above the ground, creating a virtual ceiling embedded with infra-red sensors to create a real-time data stream of user locations. The data was collected via wireless communication with a central computer that determined the speed and duration of stay and distance among people. A series of evaluation algorithms paired with rules analysed and implemented certain feedback action in animated lighting patterns that were displayed around the visitor location(s) (Fig. 12).

The additional complexity in this project lies in its capacity to collect data over longer periods of time and communicate not just passive reactions that directly translate sensor input, but instead send out intelligent signals. Protocols that were tested in the project were, for instance, to entice users to move along light pathways or to reward desirable behaviours such as closeness between two people. When the site was occupied by too many people at once, the system would display 'angry' ripple patterns to indicate to people that it wanted them to leave. There is significant potential in the further development of these systems and an intended provocation towards observers, as the system acts as a metaphor for new types of surveillance systems that are gradually being implemented within society. The scalable nature of these systems both in area size and time allows them a range of applications including office layout optimisation, public space furniture, shopping mall design, and the planning of services and infrastructure at the city scale. The output would not have to be constrained to electronic communication, but can be connected to construction methodologies as discussed in the previous projects. The high complexity of the system and limited time and means for our experiments allowed only initial testing rather than a methodical exploration of the wide range of possibilities.



FIGURE 12 'Data-Space' – field of nodes containing infra-red sensors and LEDs, tracking human activities and communicating intelligent signals.

Conclusions and Limitations

The research presented in this article explores the opportunities found within the current generation of software tools and hardware devices to set up generative on-site design and construction strategies, similar to the 'Seek' exhibition installed by MIT's Architecture Machine Group in 1970. It has focused in particular on the conceptual implications of the introduction of new technologies for the nature of the design process itself, seeing how computationally aided processes of negotiation between inhabitants and their built environment can afford more agency to inhabitants. The series of projects has shown how the monitoring of human activities can be used to inform consequential design adjustments that can be implemented directly and on-site, adapting the final outcomes better towards the intended functionalities. The later projects have shown the value of the creation of feedback loops between the mapping of human behaviour and construction implementation. They make it possible to explore strategies for fabrication where the final construction is not predetermined, but instead is producing emergent qualities based on the decisions and desires of human agency within society.

It is important to highlight the sophistication of the goals set out by The Architecture Machine Group as early as the 1970s, stating that when generative design processes or 'architecture machines' (in Negroponte's vocabulary) "can be a self-improving evolutionary specie, it sports a better chance of making its computational and informational abilities relevant" (Negroponte, 1969). These goals are much more ambitious than most parametric or generative design applications in use today, which mostly serve to manage the complexity of projects generated in traditional linear and top-down design processes. Even in the art world, which could be credited for pushing the intellectual boundaries of our relationship with new technologies more profoundly than architecture, there are very few contemporary projects that are truly 'generative' along the goals stated by Negroponte. Most installations are merely 'reactive' rather than 'interactive' and even then, the range of responses is often limited by the database of behaviour preconceived by the designers.

Our own experiments discussed in this article certainly suffer from the same limitations, as they primarily respond to site and user information in a direct, albeit mediated, way. The first two projects 'Point-Cloud' and 'Emergent Constructions' are quite direct translations of data, (without and with a specific policy of intervention), without the ability to monitor or respond to the changes in use after the intervention has been installed. Our 'Emergent Field' and 'Public Space Furniture' projects do allow for continuous feedback and adaptation to changes in site and human behaviours during the construction of the installation, yet it is a stretch to call this process 'intelligent', as it is not aware of its successes or failure at an abstract level. Another limitation of these processes is that they are incremental; they were designed to continuously grow until an equilibrium was reached. This implies that the configuration is based on a very limited data-set of monitored behaviours, which at another point in time might be much less valid. This limitation could be overcome by adding the possibility of 'un-building' into the systems, devising rules that govern the removal of previously added elements and therefore setting up a never-ending process of continuous monitoring and adaptation. The final project 'Data-Space' might have the closest relationship to Negroponte's stated goal of 'intelligent machines', if it were able to be further developed to record analyses about its own effectiveness. Since the installation has all of the necessary hardware and software components to be a fully 'responsive' environment, it could also be equipped with a communication protocol that displays some form of machine 'self-awareness' that allows it to be a 'meaningful partner' in the human-led process of adapting the built environment towards inhabitants' needs. The lighting grid in the 'Data-Space' experiment should be considered as a diagrammatic model for other forms of sensing, actuating, and activity spaces, ranging from the scale of a single room to that of an entire city. The limitations of expanded versions of the project would lie in the handling of large amounts of data, extracting meaningful conclusions in a timely manner, as has been shown to be a significant challenge in the 'smart city' area of research.

Directions and Opportunities for Future Research

There are several key potentials of using generative strategies for integrated processes of design and construction:

Design decisions may be taken in relation to a detailed understanding of a site and context, where the detailed and multi-faceted performance of a building within its environment can be experienced and tested rather than speculated upon, as is usually the case in traditional linear design processes. This should allow buildings to become better adapted to perform within their context, with high-resolution integrated functionalities and environment-specific, performance-based features.

The increased control over production offers a democratisation of design decision making and facilitates negotiation between different parties in the design process. The role of the architect using these methodologies may shift from controlling the end result to designing a process-based, quality-driven generative method, offering the freedom to adapt their living environments to the inhabitants, within certain constraints that are aimed at facilitating the construction process.

The research may increasingly incorporate intelligent behaviours, mimicking processes of self-organisation as observed within vernacular architecture and the organic development of urban settlements. Providing an alternative vision to static and idealised architectural solutions, these methodologies are able to deal with the contingencies and complexities of dynamic social, cultural, economic processes and other forms of human interaction that drive the materialisation of our architectural and urban environments.

Acknowledgements

'G-Cloud' was developed by Jeroen van Ameijde in collaboration with Brendon Carlin.

'Emergent Field' was developed by Jeroen van Ameijde in collaboration with Jenny Hill and Dennis Vlieghe.

'Public Space Furniture' was developed by Christine Cai, Sungbin Ryoo and Ke Wang, taught by Jeroen van Ameijde and Brendon Carlin.

'Emergent Constructions' was developed by Jeroen van Ameijde, Sulaiman Alothman, Mohammed Makki, Yutao Song and Manja van de Worp.

'Data-Space' was developed by Jeroen van Ameijde in collaboration with Ping-hsiang Chen, Howard Chen, Zachary Mollica, Luis Rodil-Fernández and students.

References

- Friedman, Y. (1971). The Flatwriter: Choice by Computer. *Progressive Architecture*, no. 3, March 1971.
- Friedman, Y. & Orazi, M. (2015) *The Dilution of Architecture*. Park Books.
- Gabrys, J. (2014). Programming environments: environmentality and citizen sensing in the smart city. In *A New Apparatus: Technology, Government, and the Resilient City*. B. Braun & S. Wakefield (Eds). *Environment and Planning D: Society and Space* 32, no. 1, 2014.
- Helm, V., Ercan, S., Gramazio, F., & Kohler, M. (2012). In-Situ Robotic Construction: Extending the Digital Fabrication Chain in Architecture. In *Proceedings of the 32nd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, pp. 169-176, San Francisco, 2012.
- Lima, K. (2014). Algorithmic thinking, parameterization and sustainable urbanism: an assessment of parameters for intelligent urban design strategies. In *XVIII Conference of the Iberoamerican Society of Digital Graphics - SIGraDi: Design in Freedom*, Uruguay, Montevideo, 2014.
- Mora, L., Bolici, R., & Deakin M. (2017). The First Two Decades of Smart-City Research: A Bibliometric Analysis, *Journal of Urban Technology*, 24:1, 3-27, 2017.
- Male-Aleman, M., van Ameijde, J., & Vina, V. (2011). (FAB)BOTS, Customised Robotic Devices for Design and Fabrication. *Fabricate: Making Digital Architecture*. Cambridge, Ontario: Riverside Architectural Press.
- Mitchell, W. J., & McCullough, M. (1991). *Digital Design Media*. New York: Van Nostrand Reinhold.
- Negroponte, N. (1969). Toward a Theory of Architecture. *Journal of Architectural Education*, Blackwell Publishing on behalf of the Association of Collegiate Schools of Architecture, Inc., March 1969.
- Negroponte, N. (1970). *The Architecture Machine*. Cambridge, Mass: MIT Press.
- Negroponte, N. (1975). *Soft Architecture Machines*. Cambridge, Mass: MIT Press.
- Orazi, M. (2015). The Erratic World of Yona Friedman, in Yona Friedman, *The Dilution of Architecture*, op. cit., pp. 499
- Rowe, J. (1972). Life in a Computerised Environment. *Electronics Australia*, September 1972.
- Suzuki, L.R. (2017). Smart Cities IoT: Enablers and Technology Road Map. In *Rassia S., Pardalos P. (Eds) Smart City Networks. Springer Optimization and Its Applications*, vol 125. Cham: Springer
- Van Ameijde, J., & Carlin, B. (2012). Digital Construction, Automated design and construction experiments using customised on-site digital devices. In *Digital Physicality - Proceedings of the 30th eCAADe Conference - Volume 2*, pages 439-446, Prague, Czech Republic.
- Van Ameijde, J., Carlin, B. & Vlieghe, D. (2012). Emergent Constructions, Experiments towards generative on-site design and build strategies using customised digital devices. In *Proceedings of the 32nd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, pp. 539-545, San Francisco.

