Generative Architectural Design and Build Strategies based on the Mapping of Human Behaviour

J.B. van Ameijde[a]

[a]Architectural Association School of Architecture, London, United Kingdom
E-mail: ameijde_je@aaschool.ac.uk

Abstract –

The introduction of robotics in construction offers the possibility of implementing design processes that incorporate unforeseen levels of complexity. Not only does this allow for the construction of high degrees of formal differentiation, but for the conception of projects with a high-resolution integration of performative qualities. These performance aspects can include environmental and economical properties but also social and cultural mechanisms, which can be monitored through the tracing of human activities within architectural and urban spaces.

This research presented here focuses on technologies and work flows that enable on-site data collection and construction implementation, in separated design and build phases or in an integrated process with continuous feedback. It discusses a series of small projects that explore new scenarios for the creation of architectural structures, experimenting with mobile and low-cost fabrication devices, connected to generative design algorithms driven by sensory technologies. These projects show that instead of working directly with the geometry of the final outcome, architects can begin to script individual and unique processes for generating structures, using rule-sets that capture the intelligence and underlying logic of materiality, organisation and spatial performance.

We advocate a new 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; Human Activities Monitoring; Computational design; Emergent design; Custom robotic devices; Digital construction;

1 Introduction

As robotic fabrication and assembly devices are being introduced to construction sites, it becomes possible to re-think the entire process of how architectural projects are materialised. Construction processes no longer rely on inefficient communication protocols towards manual workers and manual tools but can directly be connected to digital 3D models created by the design team. This could increase quality, reduce errors and cost, and potentially reduce construction time. It could also be used to deliver projects of increased complexity, due to the system's ability to perform large amounts of operations at high precision. As robotic devices are becoming mobile and able to work 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 direct communication between design software and construction technologies signifies a fundamental shift in the possibilities of design, as 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, there is the much more radical opportunity that presents itself: the incorporation and integration of several layers of functional complexity.

The architectural design, and therefore the design process as well, could start to incorporate complex properties of a building's performance within its environment, generated 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 and this is indeed one of the great potentials of digital design processes, to deliver increased building quality, efficiency and improved spaces designed around human comfort. But performance analysis can also be applied to how buildings perform within their socio-political context, from an economical perspective or as an environment for human circulation and inhabitation. Within the practice of planning office layouts 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, taking into account 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 be the driving force behind the rapid development of data-driven design, there is an opportunity and arguable an obligation of academics and practitioners within the architectural discourse to critically examine the possible positive and negative consequences of these new processes. The monitoring of people's behaviour through CCTV, online communication and mobile devices might have a potential dystopian dimension, but if done in an appropriate and acceptable manner, this could offer a wealth of knowledge to architectural and urban design processes. Instead of focusing on the commodification of user data for profit driven operations, architects and planners could calibrate their designs towards social interaction, human comfort and health. Where architectural and urban spaces are required to house social activities and community formation, generative design processes can be used to monitor human behaviour and define the properties and organisation of spaces to stimulate this in the most effective way. Data-driven 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.

2 Precedents: Mapping human behaviour

One example of research into the social dynamics of public spaces is the work by sociologist William H. Whyte, who's publications include The Social Life of Small Urban Spaces (Whyte 1980). His aim was to understand why certain plazas remain empty and unused, while others were well loved and heavily used as leisure spaces and social condensors within the city. He used manual techniques of measuring, counting, mapping and other forms of direct observation to understand the relationships between specific physical characteristics of the space, and the human activities that would occur. His work resulted in design guidelines on principles such as visibility, accessibility, seating, greenery and environmental conditions such as sun and wind, many of which were consequently applied by municipal governments in different cities in the United States. Whyte served as a mentor to Jane Jacobs, who wrote The Death and Life of Great American Cities (Jacobs 1961), which famously argued for the conservation of organically grown neighbourhood qualities, recognising the value of the rich mix of complementary programs that emerge around walkable neighbourhoods.

A continuation of research into the underlying principles of human decision making within urban environments can be found amongst the highly varied initiatives that can be considered part of the 'smart city' movement, that has been referenced by academic and professionals in various locations in recent time. The idea of a ‘Smart City’ was first introduced in the 1990’s but has recently attracted more high-profile projects and attention, resulting in several projects and policies that are being executed 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 is also aimed at the economic and political frameworks that guide urban development. ‘Smart City’ projects aim 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 potential positive ambitions of these project to improve sustainability but also warns of the potential dangers of monitoring and managing data on citizens. Referencing 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 'bio-political 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.

3 Methodology: Generative Design

This paper will present a series of small projects undertaken in the context of various academic research and teaching programs at the Architectural Association in London, organised under a larger research agenda into generative design and build processes based on the mapping of human activities.

The practice of generative design is well established within multiple design and engineering disciplines and can be defined as a computational design process aimed at creating the best possible solution towards specific performance criteria. It can be considered a sub-category of the larger field of parametric design, which is a terminology that merely indicates that certain parameters or relational modelling techniques are considered during a design process. The practice of generative design assumes that there are clear goals for the design solution which makes it particularly suited to be conceived as data-driven design, evaluating potential design options against detailed contextual information.

The potential role of generative design processes has been identified early on by Mitchell and McCullough (1991), who contemplated the implications of computational processes being able to address a complexity of parameters and interactions, much greater than could be handled by human cognitive processes alone. They emphasized however that instead of promoting 'automated design procedures', there remains a central role of the designer's intellectual capacity, using critical judgement towards the employment of algorithms, the input of data parameters and the definition of the evaluation criteria. Generative design in this context is employed as operating on the underlying relationships rather than 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 and Kós 2014).

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

3.1 Project 1: 'Point-Cloud'

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

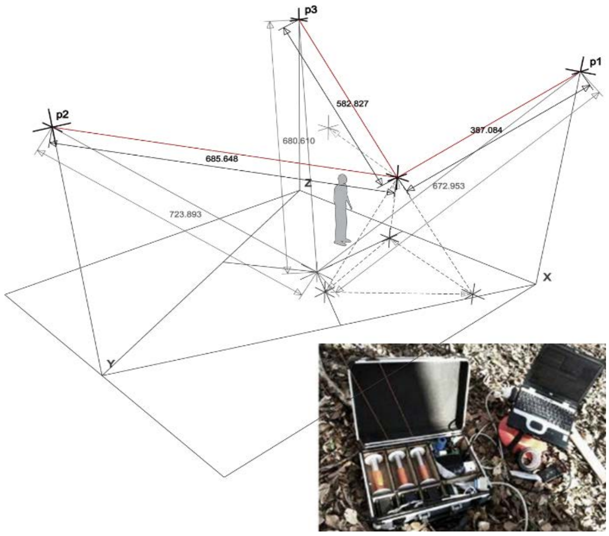

Figure 1. CNC cable robot, used as point indication device

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 computer numerically control (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 to move the wire pointer to a specific coordinate in 3D space similar to how the cutting head is moved around on a three axis CNC milling machine (Figure 1).

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 over a time period of 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 (Figure 2). 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.

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

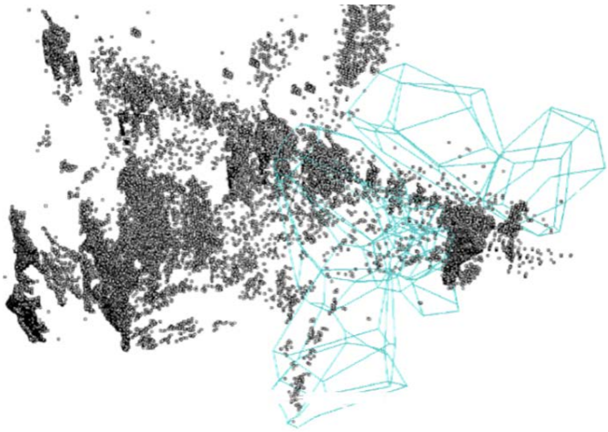

Figure 2. 3D scans of people movements through the site, translated into a triangulated structure through a generative design process

information from a digital model containing three-dimensional point locations onto a 1:1 building site. The human collaborators did tasks which they can do better than machines, such as the manual handling and connecting of building elements (Figures 3 and 4).

Figure 3 and 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 attempt to change or contribute additional functionalities related to the movement within the site. Successive projects have been set up to incorporate this ambition, not just responding passively to the data gathered on site but aiming to introduce improvements to the conditions found.

3.2 Project 2: 'Emergent Constructions'

The second project within our line of research consisted of a medium sized architectural pavilion designed to offer a temporary cluster of spaces and seating elements to visitors of a large shopping mall in Kuwait. Using digital cameras to record the movement of people 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 was translated into the design of a pavilion that would create an intervention on the existing site. This intervention would generate activity, intervene with 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 (Figure 5).

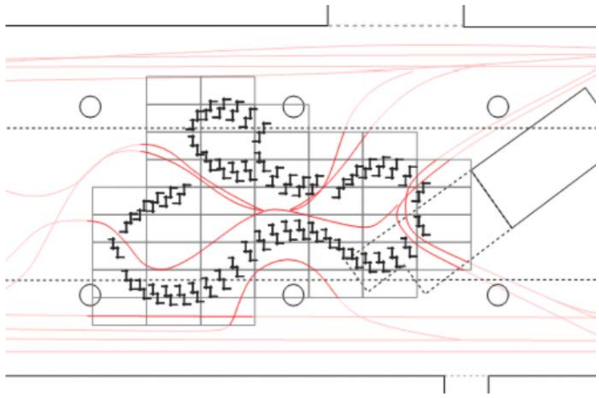

Figure 5. Pavilion space constructed through louvre walls that mediate privacy

The qualities of space that result 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 result of the generative design and construction exercise was a pavilion that manifest 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 (Figure 6).

The pavilion as a field of elements with different heights, density and functions created a varied architectural landscape that has specific intentions for

Figure 6. Pavilion spaces designed to separate visitors from the surroundings and stimulate social interaction

stimulating social interaction built into it. The multiple possibilities of use and interpretation however allowed the users to create their own social patterns and interactions, exploring 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 over-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 something that is explored further in the subsequent projects. This research follows on from an important precedent titled "Seek", exhibited in Jewish Museum in New York in 1970 by Nicholas Negroponte.

This installation consisted of a glass display case filled with small cubes that could be rearranged by a robotic arm connected to a camera and computer system. The display was inhabited by gerbils, who continuously moved the cubes around. The robotic arm was used to help organise the arrangement of the cubes, not according to a fixed blueprint but based on rules that tried to interpret the preferences of the gerbils. Throughout this process over time, the aim was to let an ideal inhabitable landscape design emerge out of the negotiation between the inhabitants and their environment.

3.3 Project 3: 'Emergent Field'

The third project titled 'Emergent Field' explored a similar generative, rule-based design strategy that monitored people movement through a particular forest site and materialised this as a field of timber sticks placed vertically within the terrain. This material system was chosen for its ease of construction and the compatibility of the geometries with the CNC controlled device that was going to be used, which was the same cable robot device as introduced in project 1, described previously. The vertical nature of the sticks would allow the wires of the cable robot to be moved in between 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 would enable the system to build additional pieces inside areas that had already been populated with sticks.

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 towards the build area was used to take snapshots over a period of time of people locations. A simple piece of software was used to process the images, selecting areas of red colour as all people in the experiment were asked to wear red head coverings. The recorded site occupation density patterns were automatically translated into geometrical patterns for the timber stick formations using a generative design process based on simple rules (Figure 7). The movements were recorded during breaks in between the building activities, when people were asked to freely pass through, explore or inhabit the forest site.

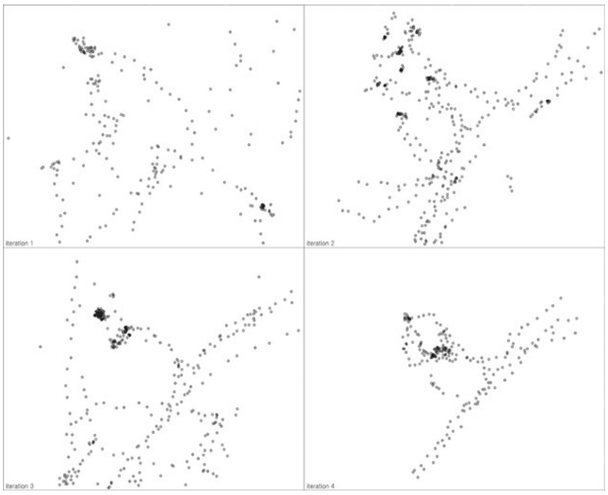

Figure 7. Density maps generated by web-cam monitoring of people, showing the iterative refinement of pathways and hangout spaces

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 sticks. The initial layers of elements within the site were placed with a generous spacing, in order to allow users to move in between the sticks that were

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

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 informed through the active negotiation between material and users around the real experience of the installation in the site (Figure 8).

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 'friezing' a data-set containing site information, the relevant parameters are continued to be monitored throughout the construction process, allowing to 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.

3.4 Project 4: 'Public Space Furniture'

The fourth project continued to build on to 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 was used to record people inhabiting the terrace, documenting their position, duration of stay and distance to others (Figure 9). 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 place furniture in positions that would encourage social interaction between people or instead create separations in between different people. The experiments produced emergent outcomes where an architectural structure would grow over time without predetermined design. Users interacted with the structure through sitting, leaning, placing coffee cups, etc. and generally staying longer and engaging in different activities than they would have normally done within this site.

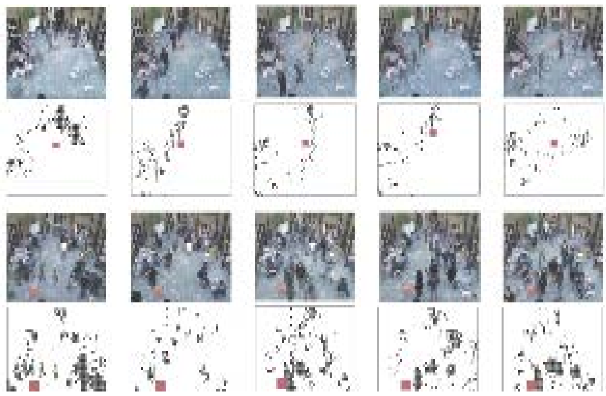

Figure 9. Snapshots of people monitoring as seen through the web cam and as analysed by blob-tracking algorithms

An initial furniture system was implemented using plastic crates, which led to increased social interaction within the site and engagement of the visitors with the experiment. In the second phase, a custom designed CNC fabricated furniture system was deployed that allowed for cantilevering elements and incorporated open and closed panels to be able to block sight lines and create privacy (Figure 10).

Figure 10. 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 high amount of variables in the experiments makes it difficult to evaluate with precision which rule-sets or furniture configurations are more effective than others, and the project was mainly intended as a proof of concept that this type of process could be built.

3.5 Project 5: 'Data-Space'

The fifth and most recent project in the series is by no means a final development as it was intended to offer even a higher degree of speculation and open up additional avenues of contemplation about continuous monitoring and feedback systems embedded within the built environment. Titled 'Data-Space', it was developed by the author in collaboration with 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, allowing monitoring and communication 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 in a central computer, that was able to determine the speed, duration of stay and distance in between people. A series of evaluation algorithms were paired with rules for analysis and implementation of certain feedback action, in the form of animated lighting patterns that were displayed around the visitor location(s) (Figure 11).

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 to be applied to 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 11. 'Data-Space' – field of nodes containing infra-red sensors and LED's, tracking human activities and communicating intelligent signals.

4 Conclusions and Future Research

The research presented in this paper explores the conceptual opportunities found within the integration of sensors, material growth systems and robotic devices into generative on-site design and construction strategies. It has focused in particular on the conceptual implications of the introduction of new technologies for the nature of the design process itself, the changing role of the architect and the potential attitude towards processes of negation between inhabitants and their built environment.

It has shown how the monitoring of human activities can be used to inform consequential design adjustments that can be implemented right away, adapting the final outcomes better towards the intended functionalities. By creating feedback loops between the mapping of human behaviour and construction implementation, it is 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.

There are several key potentials of this new approach towards 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 from behind the screen of a computer. This should allow buildings to become be 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, allowing successful methodologies to be implemented towards a range of programs and sites.

The research may increasingly incorporate intelligent behaviours, mimicking processes of self-organisation as observed within nature or in the growth and adaptation of cities. 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.

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