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Apparatisation in & of Architecture

Sang Lee, Henriette Bier

Department of Architecture
Delft University of Technology

Apparatus and apparatisation, the focus of the Cyber-Physical Architecture (CpA) issue #2 of SPOOL, refer to an assemblage of various components, tools, and instruments that in combination produce an exponential surplus beyond the linear sum of parts. On the one hand, apparatus can be seen as a collective of means used to perform certain tasks in order to solve a range of problems. It can contain a series of tools and instruments and produce new rationalities that often translate into pervasive technology, such as, for instance, electricity and, today, Information and Communication Technology (ICT). On the other hand, apparatuses can be found in organisations and institutions that deal with various aspects of a society. For example, the police apparatus, of which rationalities are – rather than being embodied in physical technics – codified in written statutes. The apparatus in this sense is a collection of performative concepts that the subjective members of the apparatus execute in order to serve policies and plans.

In the context of the foregoing views of apparatus, architecture consists of both technics and concepts in design, construction, and use that have accumulated for generations. It has developed its canons through inherited practices (i.e. the conventions that have been established over time, or simply the way it has been done according to the tradition) that conflate the two in relation to the dominant forces (ideological, political, cultural, social, economic, etc.) of the time.

Architecture and its urban conditions result from particular interconnected discourses, attributes, and practices that are conceived, instantiated, and materialised in a given period. Architecture as a discipline consists of relations and agency of its instruments (drawings, models, and specifications), which are directed at determinate configurations and situations, as well as objects.

The substance of a given apparatus of architecture is determined by the relations and trajectories between what is explicit (drawings and notations, specifications and writings of all sorts, which in some manner bracket a given project) and implicit (strategies, intentions concerning desired effects or affectations, preferences, etc.). Given its inevitable public presence and the assumptions of *accommodating* human occupancy and use, architecture is necessarily circumscribed by the relations of institutions, ideologies, politics, economics, personalities, and so forth. This ensemble of relations determines the spatialising and the ordering and organising of social multiplicities.

Apparatisation in and of architecture relates to architects' capability to produce and exercise a new field of rationalities through instructional and notational instruments (digital), rather than remaining in the inherited practice (analogue) of design and construction. The historically entrenched view of architecture as inherited practice indicates that an architect creates an autonomous world and that the participants in the work dwell in that world. Today, our spatial world is situated within the rationalities of the pervasive apparatus that spans and blurs the actual and the virtual.

With the advent and proliferation of digital algorithmic apparatus, architecture has become thoroughly apparatised. The cognitive, intellectual capacity of the architect as author no longer commands the aura the disciplinary tradition has endowed. Its disciplinary rationalities have come to include increasingly transdisciplinary elements, modalities, and attributes. At the same time, it is also highly specialised to the extent that the historical autonomous authorial view of the discipline is neither needed nor tenable.

When considering the dependencies on highly specialised knowledge and skills at the core of such apparatisation, architects are confronted with a new class of skills, expertise, and knowledge. The apparatus-centric systems fundamentally alter the relationship between episteme and techné. The study and practice of architecture is no longer dominated by mastering and applying canonical knowledge, but instead, by apparatus-centric potentials for new rationalities. Such apparatus-centricity should, in principle, encourage alterity and dissent, rather than similitude and conformity, in order to create new commons of knowledge.

The CpA #2 samples various interests afforded by the apparatus and apparatisation in and of architecture and how they open up new potentials and opportunities. The first article, *Building as Apparatus?* (by Leach) addresses the theme of "buildings-as-apparatus" through theoretical and historical discussions on politics, control, agency, and social impact by Foucault, Deleuze, and others. Leach argues that the architectural object in itself has no agency and the term "apparatus" should be understood as an embodiment of a larger system of culture, politics, and practices in which buildings can be a constituent part.

Architecture Machine Revisited (by van Ameijde) summarises a series of experiments organised at the Architectural Association between 2011 and 2017. The experiments investigate the intellectual notion of "the architecture machine" introduced by Nicholas Negroponte and the Architecture Machine Group (AMG) at MIT in 1967. The article focuses on technologies and work-flows that trace human activities and translate them into architectural structures as initiated by the AMG.

Discreet Robotic Assemblies (by Garcia, Retsin, and Soler) questions the acceptance of a continuous paradigm within robotic fabrication and proposes a model based on a discreteness, in which building elements are combined into larger assemblies, rather than being described by the rationalisation of a whole. *Structural Adaptation* (by Hidding et al.) explores the rationalisation aimed at improving structural performances and achieving multi-functionality, focusing on the design and robotic fabrication of a chaise longue that can change shape to function as both a bed and a chair depending on user requirements.

Finally, reflecting on today's architectural theories and practices, *Dialog #1* (by Bier and Green) discusses how high-technology as an intellectual model impacts architecture. They question the speed of implementation and the pervasiveness of high-technology in architecture in contrast to the continuation of the inherited practice.

Can a Building Be an Apparatus?

Neil Leach

Faculty of Architecture
Florida International University

Abstract

When Michel Foucault introduces the term, dispositif, commonly translated as 'apparatus', he uses the architectural example of the Panopticon to illustrate how power is exercised. A building, according to this line of thinking, seemingly has the capacity to exercise control on its occupants. But is this really the case? This paper examines the thinking of Foucault on the subject, and questions to what extent we can conceive of a building as being in and of itself an apparatus. It goes on to explore Foucault's subsequent reflections on the subject in his interview with Paul Rabinow, 'Space, Knowledge and Power', where he seems to qualify his earlier remarks on the Panopticon. It then opens up the theory of affordances to question whether a building – or any other entities that could be perceived as operating as a tool or mechanism within the social realm – has the agency to control behaviour. Finally, the paper introduces Gilles Deleuze's subsequent remarks in 'Postscript on the Societies of Control' where he contributes to the debate about the political agency of form by arguing that in our present age there has been an erosion in the hegemony of the physical, and current forms of control are more gaseous and invisible in their operations than a mere physical building. The paper concludes that it is too simplistic to regard a building in and of itself as an apparatus. At best it could be perceived as an element within a 'system of relations' that might constitute the apparatus.

Keywords

apparatus, dispositif, panopticon, control, affordance, disciplinary societies, societies of control

Introduction

Architects, it would seem, are prone to exaggerate the social impact of their profession. Indeed, Le Corbusier even believed that architecture could prevent revolution. *'Architecture ou Révolution,'* wrote Le Corbusier in 1922. 'It is the question of building which lies at the root of the social unrest of today; architecture or revolution.' (Le Corbusier, 1989). Le Corbusier, along with with many architects of the Modern Movement, was convinced of the social impact of architecture. In an era of great social and political change, he perceived architecture as a crucial instrument in addressing the ills of contemporary society. An appropriate architecture would combat social unrest. Architecture could prevent revolution.

But what capacity does architecture actually have to influence social and political life? Are architects correct in believing that architecture wields so much power, or is this simply a delusion, common no doubt in other disciplines too, where professionals in one field consider their field to have a greater potential to change the world than it actually has?

Let us focus firstly on the relationship between architecture and politics. There are many ways in which architecture might be perceived as being political. Some have attempted to 'read' a certain politics into architectural form. However, it is precisely in these semantic readings of architecture that the fragility of associations between architecture and the political become most apparent. In their discussion of 'democratic' architecture, for example, Charles Jencks and Maggie Valentine recognise the subject as problematic. They observe that neither Frank Lloyd Wright nor Vincent Scully, both of whom had written on the subject of architecture and democracy, had managed to relate the politics to any typology or style of building (Jencks and Valentine, 1987).[1] Yet while they also note that Aldo Rossi and others had claimed that there was no direct link between style and politics, they themselves persist in an attempt to define an 'architecture of democracy'. Their approach relies on semantic readings. For Jencks and Valentine, as it transpires, the problem rests ultimately in the complex 'codes' that 'democratic architecture' adopts. It must avoid excessive uniformity ('An architecture of democracy that is uniform is as absurd as a democracy of identical citizens'), yet equally it should avoid excessive variety ('an architecture where every building is in a different style is as privatised as a megalopolis of consumers.') 'Thus a democratic style,' they conclude, '. . is at once shared, abstract, individualised and disharmonious.' Jencks and Valentine emphasise the aesthetic dimension, as though this has some direct bearing on the political. Yet their argument is undone by its own internal inconsistencies. How can classical architecture symbolise both Greek democracy and Italian fascism? Can there be any essential politics to a style of architecture? Can there ever be a 'democratic architecture'?

Here we must recognise that political content in architecture must be seen as associative. Architecture can only be imbued with political content through a process of 'mapping'. Architecture achieves its political – and hence equally its gendered – status through semantic associations, which exist within a temporal framework and are inherently unstable. These semantic associations depend on a historical memory within the collective imagination. Once this memory fades the semantic associations will be lost, and the building may be re-appropriated according to new ideological imperatives. Thus, the pyramids' emblems, no doubt, of totalitarian rule to the slaves who built them, have now shifted their symbolic content to icons of tourism. A similar process inevitably occurs when a building changes its use, from Victorian villa to academic department, from police station to brothel, from dictator's palace to casino. Unless the memory of its previous social use is retained, all earlier associations are erased. While a building, through its associations,

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[1]   For Vincent Scully on architecture and democracy see: Vincent Scully, Modern Architecture: The Architecture of Democracy, New York: George Braziller, 1974; for Frank Lloyd Wright on the subject see: Frank Lloyd Wright, An Organic Architecture: The Architecture of Democracy, London: Lund Humphries, 1939; When Democracy Builds, Chicago: University of Chicago Press, 1945.

might appear as deeply political, it must be understood that these politics are not an attribute of the architectural form itself. Political content does not reside in architectural form. It is merely grafted on to it by a process that is strictly allegorical. To perceive the political meaning, one has to understand the allegorical system in which it is encoded. Yet this is not the allegorical system that one might identify, for example, with Renaissance painting, where allegory relies on a narrative of fixed symbols with which the painter works. The allegory to which I refer is an allegory of association. A closer comparison, therefore, might be the way in which abstract painting has been read as political, and promoted by the CIA – so the story goes – as a tool of post-war propaganda.

Fredric Jameson highlights the problem of the allegorical nature of this 'mapping' of the political onto the architectural. Whatever political content might seem to be invested in architectural form may subsequently be erased or rewritten:

I have come to think that no work of art or culture can set out to be political once and for all, no matter how ostentatiously it labels itself as such, for there can never be any guarantee that it will be used the way it demands. A great political art (Brecht) can be taken as a pure and apolitical art; art that seems to want to be merely aesthetic and decorative can be rewritten as political with energetic interpretation. The political rewriting or appropriation, then, the political use, must be allegorical; you have to know that this is what it is supposed to be or mean – in itself it is inert (Jameson, 1997).

Rather than exploring semantic readings of the politics of architecture, we might therefore do better to explore the potential of architecture to influence a certain politics of use through its physical layout and form. Here it might be useful to step outside the discourse of architecture itself, and engage with the ideas of the French philosopher, Michel Foucault, on the subject.

Foucault and the Logic of the Apparatus

'Dispositif' is a term introduced by Foucault.[2] Loosely, it could be translated into English as 'apparatus'. In an interview in 1977 Foucault defines it as follows: 'What I'm trying to pick out with this term is, firstly, a thoroughly heterogeneous ensemble consisting of discourses, institutions, architectural forms, regulatory decisions, laws, administrative measures, scientific statements, philosophical, moral and philanthropic propositions – in short, the said as much as the unsaid. Such are the elements of the apparatus.
The apparatus itself is the system of relations that can be established between these elements' (Foucault, 1980). As Foucault states clearly enough, architectural forms are 'elements' of the apparatus. Within the constraints of this article, however, the challenge is to examine whether or not a building in and of itself can be considered an apparatus, as inferred by the expression used in the call for papers, 'building-as-apparatus'.

One of the central preoccupations for Foucault is the relationship between power and space, and he throws some light on this issue in his discussion of Bentham's Panopticon. The principle that Foucault is trying to illustrate is that the architecture may be perceived as being part of an apparatus for 'creating and sustaining a power relationship independent of the person who operates it.' (Foucault, 1979). In this now-famous piece, Foucault explores the question of how architectural form may influence social behaviour. The Panopticon is a plan for a disciplinary enclosure. This might be a prison, school, or hospital. The precise function of the space

[2]   Dispositif is a term that has been picked up by others, notably Italian philosopher, Giorgio Agamben, and elaborated further. This article, however, will be restricted to an overview of Foucault's understanding of the term.

is not as important as the fact that it is designed to accommodate some kind of disciplinary operation. What is highly important, however, is the spatial arrangement of the structure.
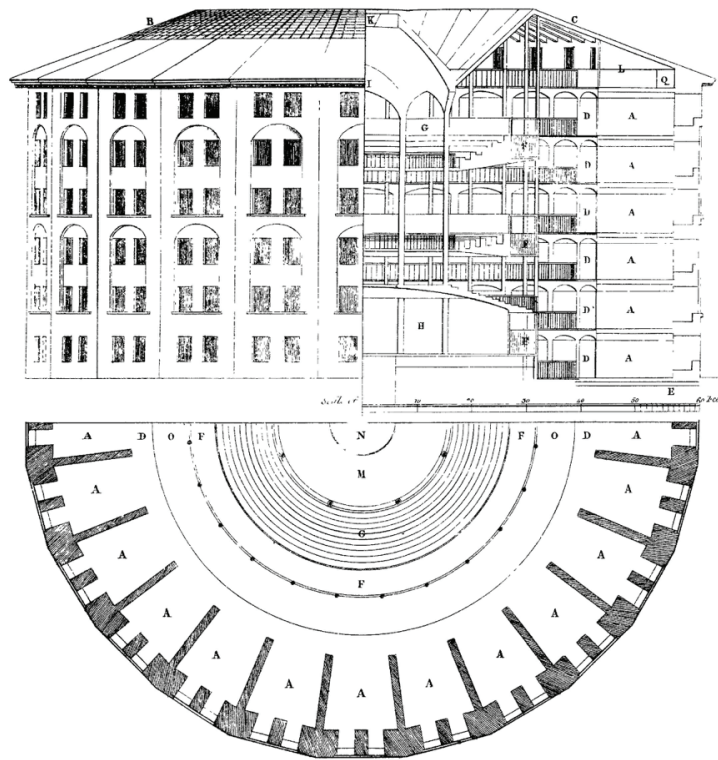
The Panopticon has a central tower in which the guard sits, and the cells are arranged radially, so that from the tower the guard is afforded a view all around – as the name 'Panopticon' implies – into each of the cells. Meanwhile, the openings in the tower itself, through blinds and other devices, prevent the inmates in the cells from knowing whether or not the guard is watching them. Thus, the inmates remain under the perpetual control of the gaze of the guard. As Foucault notes, 'Hence the major effect of the Panopticon: to induce in the inmate a state of conscious and permanent visibility that assures the automatic functioning of power.' (Foucault & Leach, 1997).

The arrangement therefore leaves the inmates under a perpetual state of potential surveillance, and serves, according to Foucault, to subjectify the inmates and turn them into docile subjects. For Foucault, it therefore operates as a 'diagram' for the way in which 'disciplinary societies' operate. However, the lateral division of the cells into hermetic units also prevents any communication with the neighbouring cell, and therefore further enhances the potential exercising of control: 'Each individual, in his place, is securely confined to a cell from which he is seen from the front by the supervisor; but the side walls prevent him from coming into contact with his companions. He is seen, but he does not see; he is the object of information, never a subject in communication. The arrangement of his room, opposite the central tower, imposes on him an axial visibility; but the divisions of the ring, those separated cells, imply a lateral invisibility. And this invisibility is a guarantee of order.' (Foucault & Leach, 1997).

This arrangement functions successfully irrespective of the nature of those contained in the disciplinary structure.[3] It is a 'figure of political technology that may and must be detached from any specific use.' (Foucault, 1997) Although its most obvious use would be as a prison, the Panopticon could equally serve as a hospital, a lunatic asylum or indeed a factory: 'If the inmates are convicts, there is no danger of a plot, an attempt at collective escape, the planning of new crimes for the future, bad reciprocal influences; if they are patients, there is no danger of contagion; if they are madmen, there is no risk of their committing violence upon one another; if they are schoolchildren, there is no copying, no noise, no chatter, no waste of time; if they are workers, there are no disorders, no theft, no coalitions, none of those distractions that slow down the rate of work, make it less perfect or cause accidents.' (Foucault, 1997). Moreover, its contemporary manifestation could take the form of CCTV cameras, or speed cameras on a motorway. In the latter case, the motorist is oblivious as to whether s/he is actually under surveillance but is often forced to monitor his/her speed for fear of receiving a fine.

The real success of the Panopticon is not only that it is highly efficient in terms of personnel needed to make it function, but also that it moves beyond the limitations of a simple enclosure. The heavy bulk of an architectural form dedicated solely to incarceration gives way to a more sophisticated combination of surveillance and architectural form: 'The heaviness of the old 'houses of security' with their fortress-like architecture, could be replaced by the simple, economic geometry of a 'house of certainty'. (Foucault, 1997).

Moreover, the structure contributes to a system whereby the inmate becomes complicit in his own subjectification: 'He who is subjected to a field of visibility, and who knows it, assumes responsibility for the constraints of power; he makes them play spontaneously upon himself; he inscribes in himself the power relation in which he simultaneously plays both roles; he becomes the principle of his own subjection.' (Foucault, 1997).

At first sight, then, Foucault would seem to be arguing for the capacity of a building to engender a form of social control that would somehow guarantee the subjectification of the subject. This would hardly appear controversial to a profession, which subscribes largely to the somewhat utopian views espoused by Le Corbusier on the capacity for architecture to effect social change. But are things quite as they seem at first sight?

The Problem of the Diagram

One of the key signs that Foucault's discussion of the Panopticon is not quite as straightforward as it might first appear to those with an architectural background is the fact that he refers to the Panopticon as a 'diagram'. Foucault's interest in the diagram is influenced partly by Leibnis who celebrates diagrammatic thinking as a form of reasoning based on visual representations. This helps us to understand what Foucault means when he refers to the Panopticon as a 'diagram', or – in other words – as a visual representation (in Leibniz's terms) of the exercise of power: 'But the Panopticon must not be understood as a dream building: it is the *diagram* [my italics] of a mechanism of power reduced to its ideal form.' (Foucault, 1997).

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[3]   Although Bentham's Panopticon was never built, the principle of the layout can be seen in numerous buildings, such as James Stirling's Seeley History Library, Cambridge. Here the control desk is positioned centrally, with all the desks and shelves are laid out radially around it, affording an unobstructed view and allowing the librarian to monitor the entire space. A more sophisticated form of panopticism operates with close circuit surveillance cameras.

What makes this example of the Panopticon so interesting is that it reverses the traditional role of the diagram. Whereas a diagram is commonly used by architects to explain a design for a building, here the building itself serves as a 'diagram' – as an explanatory device – that articulates the way in which power operates. Importantly, this should alert architects to the fact that the 'diagram' to which Foucault is referring is quite different to the standard notion of the diagram in architectural culture. It might even be helpful to suggest an alternative term, such as 'model' or 'allegory', instead of 'diagram', invested as it is with so many architectural associations.

In the late 1990s there was a brief but intense interest in the theme of the 'diagram' within certain high profile circles of architectural theory. This interest was grounded in certain remarks about the 'diagram' to be found not only in the work of Foucault, but also of another French philosopher, Gilles Deleuze, who often worked in collaboration with Felix Guattari. To anyone with little background in the work of Foucault and Deleuze it would appear that – in addressing the diagram – they are talking about something very familiar to architects. After all, the diagram has long been a part of architectural discourse. But are architects and Deleuze really talking about the same thing when they refer to the 'diagram'? By extension, we should also ask whether the standard architectural interpretation of the 'apparatus' is anywhere close to Foucault's understanding of the term.
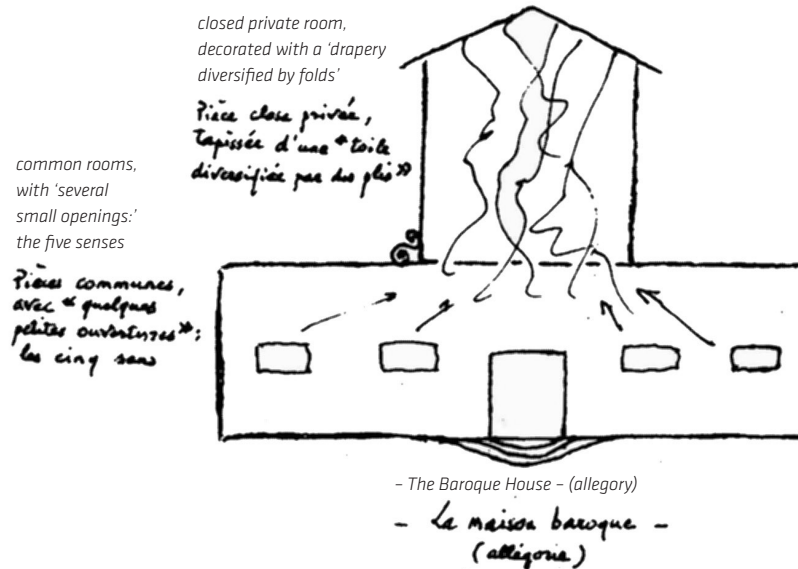
FIGURE 2 La Maison Baroque (Source: Gilles Deleuze, *The Fold* (1993)).

Not only does Deleuze write extensively about 'diagrams' in *The Fold*: *Leibniz* and the *Baroque* and elsewhere, but he also employs actual diagrams to illustrate his ideas (Deleuze, 1993). Although, at first sight, Deleuze's use of the term seems to be similar to architects' use the term, it soon becomes clear that it is quite different. For example, his diagram of the Baroque house (also referred to as 'an allegory of the monad') looks like a cross section through a building. However, as Greg Lambert explains, far from being any kind of architectural drawing or diagram, it is really an 'allegory' used to theorize the baroque construction of the conceptual pair: reading-seeing. Without dwelling on Lambert's insightful explanation of the allegory, it is clear that this is neither a diagram in the conventional sense, nor does it have anything to do with architectural form. It is an allegory of philosophical concepts (Lambert, 2002).

There is, however, a further way in which Deleuze uses the concept of the 'diagram'. In his text, Francis Bacon: The Logic of Sense, Deleuze uses it as a strategy to initiate a painting. Here the diagram – or 'graph' as Bacon calls it – serves to disrupt the given conditions and open up the space of the imagination[4]. The 'diagram', as a strategy for developing a painting, seems to be based on chaotic and random actions – generative techniques that allow the artist to break free of conventions. Whether or not Deleuze is convincing in this incursion into the domain of painting, this further use of the 'diagram' opens up yet another possible meaning of the term that is radically different to Deleuze's other uses of the term. The diagram is no longer an explanatory visualisation but a generative tool. It is not a visualisation of the use of power, as in the case of the Panopticon. Nor has it anything to do with explanation, as suggested in Deleuze's own use of literal diagrams. Rather, it refers to a projective or generative technique within the field of art that is clearly related to his other notion of the 'abstract machine', as that which actualises the 'virtual'. As Deleuze notes: 'The diagrammatic or abstract machine does not function to represent, even something real, but rather constructs a real that is yet to come.' (Deleuze & Guattari, 1987).

It is clear, then, that there is more than a little ambiguity in the discourse of the 'diagram'. As noted above, Foucault refers to a building itself as a 'diagram'. On the one hand Deleuze acknowledges that what he calls a 'diagram', Bacon calls a 'graph', while Deleuze himself also refers to a 'diagram' as an 'analogy'. On the other hand, there is a clear distinction between Deleuze's own use of the term to refer to an explanatory drawing – and indeed his own use of actual diagrams – and a generative technique for producing a work of art. In the end, the 'diagram' in the work of Foucault and Deleuze seems to have so many different meanings, that it is almost impossible to come up with one single over-arching definition of the term.

What is clear, however, is that for Foucault the building itself does not exercise power. Rather it is a 'diagram' for the exercise of power. If we follow the logic of Leibniz, then we might surmise that the building is only a 'visual representation' of the exercise of power. This alone should be enough to raise concern over any claim that a building in itself can be an apparatus for the exercise of power.

Space, Knowledge and Power

If, however, we are to accept the somewhat loose interpretation of the term 'diagram' in the work of Foucault as a visual representation of the exercise of power, what role exactly does the Panopticon play in the exercising of that power? And what does Foucault actually mean when he says that the Panopticon can be part of the 'thoroughly heterogeneous ensemble' that constitutes the apparatus?

Foucault revisits this question of the capacity of a building to influence social behaviour in a subsequent interview with Paul Rabinow, where he acknowledges that architects are not necessarily 'the masters of space' that they once were or believed themselves to be (Foucault, 1997). Here, Foucault appears not so much to reverse as to qualify the position on the capacity for architecture to determine social behaviour.

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[4] What does this act of painting consist of? Bacon defines it in this way: make random marks (lines-traits); scrub, sweep, or wipe the canvas in order to clear out locales or zones (color-patches); throw the paint, from various angles and at various speeds. Now this act, or these acts, presuppose that there were already figurative givens on the canvas (and in the painter's head), more or less virtual, more or less actual. It is precisely these givens that will be removed by the act of painting, either by being wiped, brushed or rubbed, or else covered over. . . For example, the head: part of it will be cleared away with a brush, broom, sponge, or rag. This is what Bacon calls a 'graph' or a diagram.' Gilles Deleuze, Francis Bacon: The Logic of Sensation, Minneapolis: University of Minnesota Press, 2003, p. 100.

On the question of whether there could be an architecture which would act as a force of either liberation or oppression, Foucault concludes that 'liberation' and 'oppression' are not mutually exclusive, and that even in that most oppressive of structures, such as the concentration camp, some form of 'resistance, disobedience and oppositional groupings' may still exist (Foucault, 1997). Moreover, liberty, for Foucault, is a practice, that cannot be 'established by the project itself', nor can it be necessarily guaranteed by the institutions and laws that are introduced in order to supposedly guarantee them:

'I do not think that there is anything that is functionally – by its very nature – absolutely liberating. Liberty is a practice. So there may, in fact, always be a certain number of projects whose aim is to modify some constraints, to loosen, or even to break them, but none of these projects can, simply by its nature, assure that people will have liberty automatically, that it will be established by the project itself. The liberty of men is never assured by the institutions and laws that are intended to guarantee them. This is why almost all of these laws and institutions are quite capable of being turned around. Not because they are ambiguous, but simply because 'liberty' is what must be exercised.' (Foucault, 1997).

There have been architects, of course, who have attempted to produce buildings 'dedicated to liberating effects'. (Foucault, 1997). Foucault cites the example of Le Corbusier as someone who had attempted to do so, despite the fact that he has been perceived by some as a form of 'crypto-Stalinist'. However, architecture cannot in itself be liberating or repressive. As Foucault comments, 'I think that it can never be inherent in the structure of things to guarantee the exercise of freedom. The guarantee of freedom is freedom.' (Foucault, 1997).

In the interview, Rabinow presses Foucault on whether there could be any example of a building that could prove liberating, but Foucault is quite adamant that buildings cannot guarantee any form of politics. Liberty is a practice and it cannot be based on the order of objects, such as buildings: 'No. It cannot succeed. If one were to find a place, and perhaps there are some, where liberty is effectively exercised, one would find that this is not owing to the order of objects, but, once again, owing to the practice of liberty.' (Foucault, 1997).

Architectural form, Foucault concludes, cannot in itself resolve social problems. It is only politics that can address such issues, although architecture can contribute in some way provided that its physical arrangement is such that it does not hinder the practice of the political. Thus, Foucault concludes: 'I think that [architecture] can and does produce positive effects when the liberating intentions of the architect coincide with the real practice of people in the exercise of their freedom.' (Foucault, 1997). Foucault is therefore not contradicting but merely qualifying his earlier comments on the Panopticon. It is not the form of the Panopticon which controls the behaviour of the inmates. Rather it is the politics of use – the fact that the building is operating as a prison, for example – which is ultimately determinant of behaviour, and the architecture is merely supporting the politics of use through its layout.

As such, Foucault makes it abundantly clear that architectural form in itself cannot exert any liberating effect. It cannot be an apparatus of freedom. The same applies to machines that can only have any impact when there is a 'convergence' between their operations and the political effects intended: 'Men have dreamed of liberating machines. But there are no machines of freedom, by definition. This is not to say that the exercise of freedom is completely indifferent to spatial distribution, but it can only function when there is a certain convergence.'

The position of Foucault on this matter is clear. In opposition to the utopian visions of Le Corbusier and others, Foucault would emphasise the politics of everyday life over architectural form as the principal determinant of social behaviour. 'The architect,' he comments, 'has no power over me. . . If I want to tear down or change a house he built for me, put up new partitions, add a chimney, the architect has no control.' (Foucault, 1997). According to such an approach, there could be no 'revolutionary' architecture in the sense

of an architecture that might constitute some critical force of change. Yet this is not to deny the capacity for architecture to 'produce positive effects' when its layout coincides with the layout required to enable a certain practice of politics. Such an approach, of course, brings an important temporal dimension into consideration. As political practice changes, so the efficacy of the architectural form to support that practice may itself be compromised.

Theory of Affordances

How are we to explain the potential of architecture to have 'positive effects' when its form seems to facilitate a certain politics of use? Let us start by stating that from a post-structuralist perspective, tools have no agency. They cannot force us to do anything. The same goes for a building. As Foucault has noted, a building cannot force us to behave in a certain way.

Indeed, one key problem for post-structuralists is that phenomenologists are often guilty of ascribing 'agency' to an object. This returns with a vengeance if we consider the controversial Actor Network Theory [ANT] promoted by Bruno Latour. ANT assumes that objects 'act' in social networks. Latour himself uses the example of a door-closer 'on strike' to illustrate his point (Latour, 1988). However, the most well-known architectural example of ascribing agency to objects is perhaps Louis Kahn asking a brick what it wants to do, as though the brick has the capacity to think and speak. "You say to a brick, 'What do you want, brick?' And brick says to you, 'I like an arch.'. And you say to brick, 'Look, I want one, too, but arches are expensive and I can use a concrete lintel.' And then you say: 'What do you think of that, brick?' Brick says: 'I like an arch.'" (Weinwright, 2013). This – for the post-structuralists – is simply a question of ventriloquism, of projecting onto the object a form of anthropomorphic agency. Of course, there is always a natural tendency to think in this way. Many of us call our cars names, and perhaps even speak to them. And, as Lacan has observed, there is a 'primordial anthropomorphism' that underpins knowledge, and he therefore questions "whether all knowledge is not originally knowledge of a person before being knowledge of an object, and even whether the knowledge of an object is not, for humanity, a secondary acquisition." (Lacan, 1975). However, from a post-structuralist viewpoint, the problem is that we end up 'appropriating' the object – be it door-closer or brick – as though we understand it.[5]

If, however, we were to look for a theory that might explain the potentialities of architectural forms to support a politics of use, we might start by considering the 'theory of affordances'.[6] The theory of affordances suggests that there is a particular action or set of actions that is afforded by a tool or object. Thus, a knob might afford pulling – or possibly pushing – while a cord might afford pulling. This is not to say that the tool or object has agency as such. In other words, the tool or object does not have the capacity to actually 'invite' or 'prevent' certain actions. Rather it simply 'affords' certain operations that it is incumbent on the user to recognise, dependent in part on a set of pre-existing associations that have been made with that tool or object. Likewise, that action or set of actions is also dependent upon the capacity of an

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5   Jacques Derrida has offered a powerful critique of the potential relativism of phenomenological hermeneutics in his analysis of Heidegger's interpretation of a painting of shoes by Van Gogh. Jacques, Derrida, Truth in Painting, translated by Geoff Bennington and Ian McLeod, Chicago: University of Chicago Press, 1987.

6   The theory of affordances was introduced initially by James Gibson in an article, James Gibson, 'The Theory of Affordances', in Robert Shaw and John Bransford (eds.), Perceiving, Acting, and Knowing, London: Wiley, 1977. Gibson later elaborated on this theory in his book, James Gibson, The Ecological Approach to Visual Perception, Hove: Psychology Press, 1979. It was also developed by Gibson's wife, Eleanor Gibson together with Anne Pick: Eleanor Gibson, Eleanor, Anne Pick, An Ecological Approach to Perceptual Learning and Development. New York: Oxford University Press, 2000.

individual to undertake those actions. Thus, certain actions might not be afforded to small children or those without the strength or agility to perform those actions. Moreover, certain tools afford certain operations, but do not preclude other operations. For example, we might perhaps affix a nail with a screwdriver – albeit less efficiently – if we do not have a hammer at hand. We might also recognise that it is easier to cut wood with a saw than with a hammer, and that the technique of cutting with a saw affords a limited range of possible operations.

Again, what applies to tools can also apply to buildings, in that both could be described loosely as 'systems' that might be used to accommodate certain actions. In other words, we might describe the architectural form of the Panopticon as 'affording' the possibility of it being used for the purpose of a disciplinary space, such as a prison. Yet the Panopticon itself has no agency. It does not force the occupants to behave in a certain way. It is the politics of use that engenders that, not the architectural form. Imagine, for example, that the logic of the Panopticon were to be reversed, such that the inmates in their cells were to *invite* the gaze. Turn the Panopticon into a dance club with the inmates gyrating in their cells inviting the gaze of those in the centre, and you have the same building operating efficiently according to a fundamentally different programme.[7]

Societies of Control

There is, however, a further concern that needs to be addressed in questioning the capacity of a building to serve as an apparatus. This concern emerges out of Deleuze's own subsequent contributions to the issues that Foucault had raised about the exercise of power. Following on from Foucault's text, Deleuze wrote a further text, 'Postscript on the Societies of Control'. Deleuze is, of course, a champion of Foucault's work, and is quick to praise his analysis of the Panopticon. However, Deleuze also notes that Foucault was also operating in a temporal framework: 'But what Foucault recognized as well was the transience of this model.' (Deleuze, 1992). Foucault recognised that 'societies of sovereignty' had given way to 'disciplinary societies'. According to Deleuze, however, 'disciplinary societies' themselves have now given way to 'societies of control': 'Foucault located the disciplinary societies in the eighteenth and nineteenth centuries; they reach their height at the outset of the twentieth. . . But everyone knows that these institutions are finished, whatever the length of their expiration periods. It's only a matter of administering their last rites and of keeping people employed until the installation of the new forces knocking at the door. These are the societies of control, which are in the process of replacing the disciplinary societies.' (Deleuze, 1992).

The factory, Deleuze notes, has given way to the corporation (Deleuze, 1992). And with it a new form of control has begun to take charge, whose shift is most obvious in approaches towards money. The fixed value of gold has given way to floating rates of exchange, just as we have shifted from spaces of enclosure to societies of control, a shift epitomised for Deleuze as one between two animals, 'the monetary mole' and the serpent: 'The old monetary mole is the animal of the spaces of enclosure, but the serpent is that of the societies of control. We have passed from one animal to the other, from the mole to the serpent, in the

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7 Here I want to introduce a new concept into the theory of the Panopticon – the concept of camouflage. If there was a weakness in Bentham's model of the Panopticon, it was perhaps that it did not allow for the potential of subterfuge. The visibility of the prisoners in front of the guards, guaranteed, according to Foucault, the subjectification and consequent docility of the prisoners, just as the operations of Big Brother would guarantee, according to Orwell, a society of control in 1984. But the other Big Brother - the Big Brother of 21st century reality television – suggests that there is an alternative strategy now at work – a strategy of deception and masquerade. The way to resist the gaze of Big Brother is perhaps to invite the gaze of Big Brother – to posit a form of compliance at least on the surface level, and yet underneath to offer a form of resistance. The logic of the burka or the Trojan Horse.

system under which we live, but also in our manner of living and in our relations with others. The disciplinary man was a discontinuous producer of energy, but the man of control is undulatory, in orbit, in a continuous network.' This leads Deleuze to conclude: 'The coils of a serpent are even more complex than the burrows of a molehill.' (Deleuze, 1992).

Likewise, we have witnessed an erosion of the hegemony of the physical. This has important ramifications for any discourse based on the logic of enclosure by a physical form, such as the Panopticon. Control now takes a less physical and more invisible form - credit: 'Man is no longer man enclosed, but man in debt.' (Deleuze, 1992).

Perhaps most importantly, however, Deleuze recognises that the regime of the apparatus that Foucault was addressing in his discourse about disciplinary societies has given way to another regime, a regime not of the mechanical tool involving energy, but a regime of the computational tool, whose modus operandi is entirely different, and more viral in its operations: 'Recent disciplinary societies equipped themselves with machines involving energy, with the passive danger of entropy and the active danger of sabotage; the societies of control operate with machines of a third type, computers, whose passive danger is jamming and whose active one is piracy and the introduction of viruses.' (Deleuze, 1992).

Conclusion

This brings us back to the question of the apparatus. What becomes clear is that in and of itself a building cannot act as an apparatus. At best, in Foucault's terms, it can operate within a 'system of relations' that might be established between various elements that might include – or equally might not include – architectural forms. It is this 'system of relations' that constitutes the apparatus. Rather than referring to a building as 'apparatus' we might therefore refer to a building as 'a constituent element within a system that constitutes an apparatus'.

There is, however, a further issue that is raised by Deleuze on the model that Foucault is proposing. If we are to link Foucault's discourse on the apparatus with the specific model of the Panopticon, which he uses to illustrate the operations of the apparatus, we have to accept that the model belongs to the 'disciplinary societies' of the 18th and 19th centuries and does not apply to the 'societies of control' that now exists in the 21st century. Moreover, according to that logic, the mechanistic logic of the Panopticon has given way to the viral logic of the age of computation, an entirely different logic.

As such, we might further qualify our comments on the capacity for a building to operate as 'a constituent element within a system that constitutes an apparatus', in that even this is contingent on the temporal framework in which we are operating. It is therefore clear that any unconditional claim that a building can operate as an apparatus is deeply flawed.

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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 outs 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).
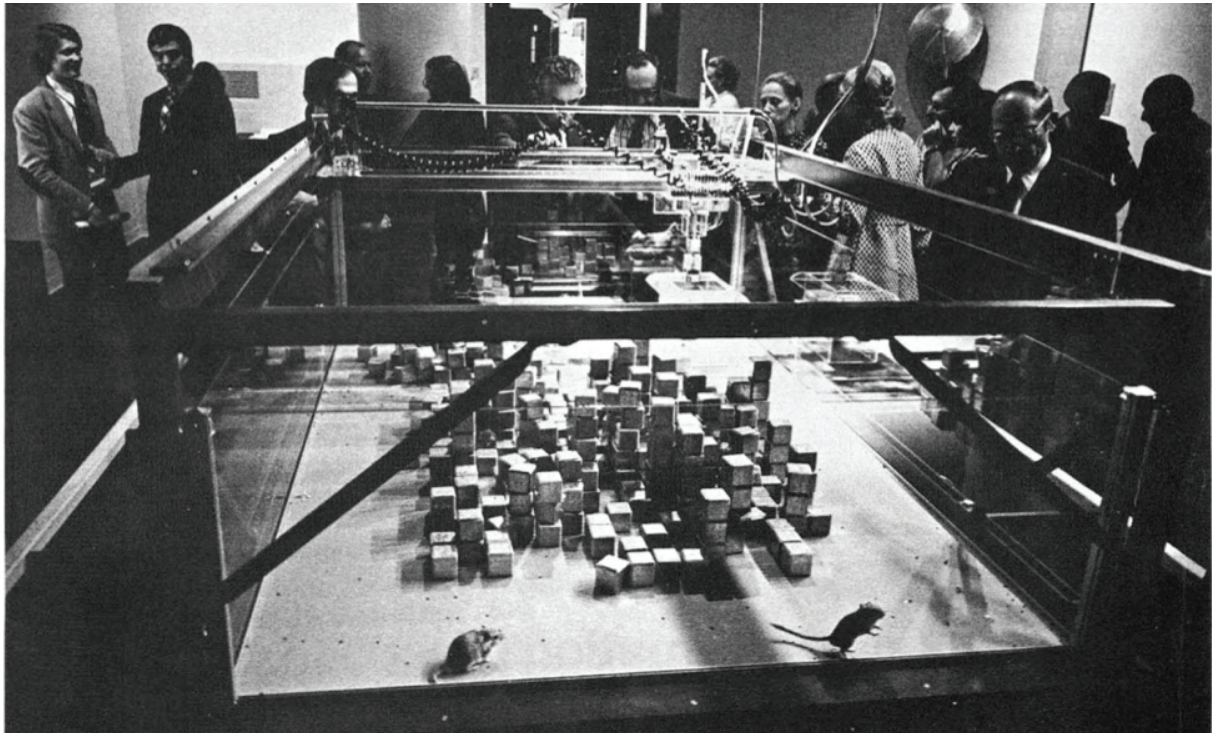

FIGURE 1 Seek' installation by Nicholas Negroponte and The Architecture Machine Group, 1970.

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 '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.

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).
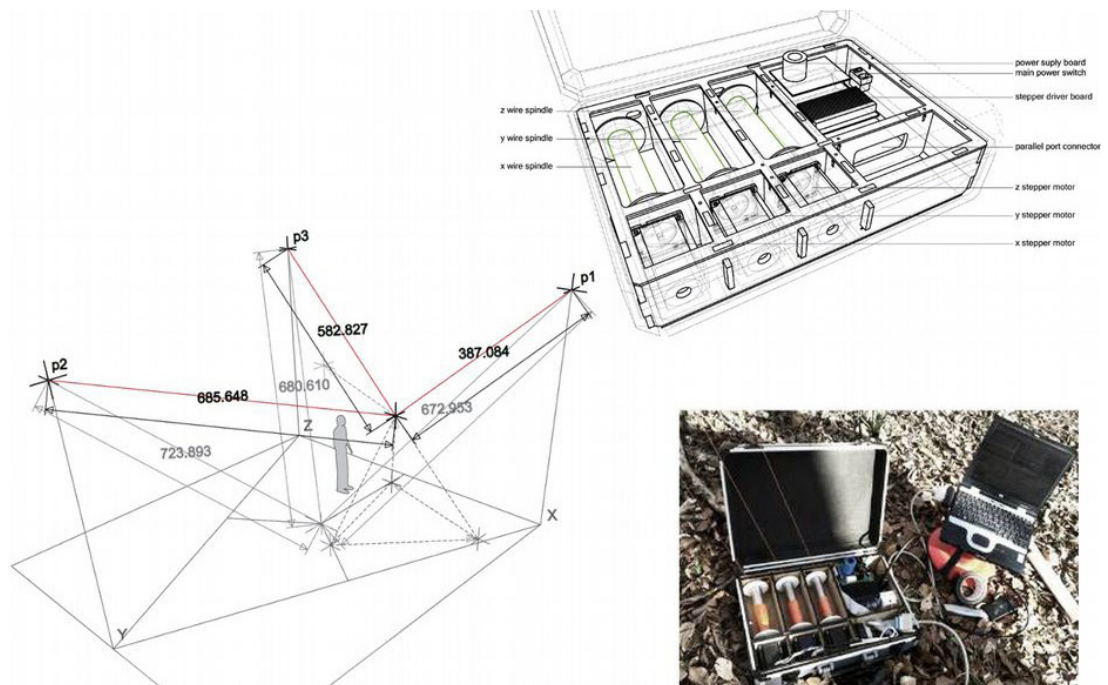

FIGURE 2 CNC cable robot used as point indication device.

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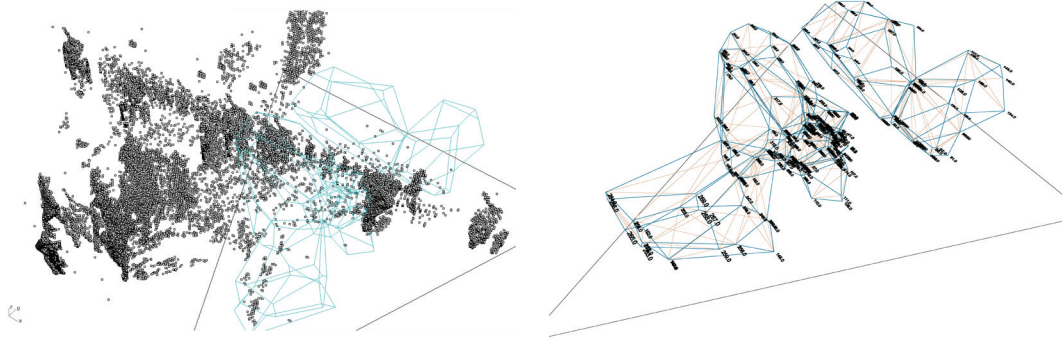
FIGURE 3 3D scans of movements of people through the site, translated into a triangulated structure through a generative design process.

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).

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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).
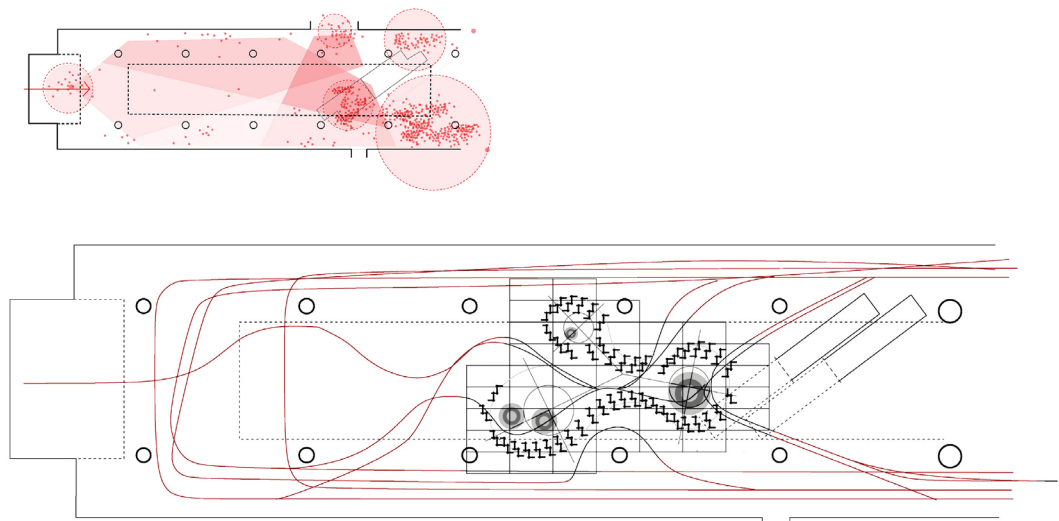

FIGURE 5 Louvre walls enclosures generated in relation to visitor intensities and sight lines.

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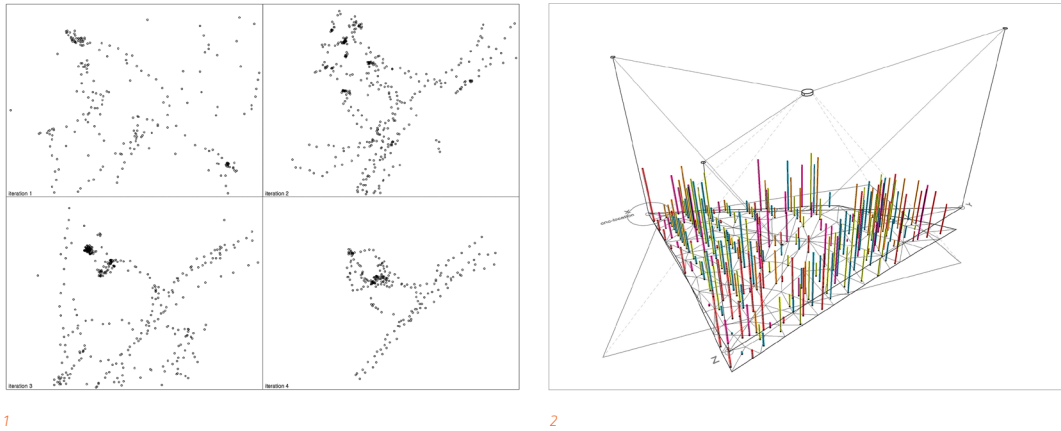
FIGURE 7 Density maps and timber pole patterns generated by web-cam monitoring of people, showing the iterative refinement and densification around pathways and hangout spaces.

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 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, 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

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Discrete Robotic Assemblies

Towards an automated architecture

Manuel Jiménez García, Gilles Retsin, Vicente Soler

Bartlett School of Architecture
University College London

Abstract

The projects featured in this paper aim to demonstrate the potential of Discrete Robotic Assembly in architecture. Although still in its early stages, this research proves that there is an increase in construction efficiency within a discrete design framework. The research shows how a limited set of assembly possibilities eases the automation of the manufacturing process and leads to a reduction of labour, construction time, and cost. This intrinsic link between discrete design methods and automation hints at a potential shift in the construction industry governed by a new paradigm in computational design, where architectural elements are defined from and for automation.

Keywords

robotic assemblies, automated architecture

Introduction

The use of industrial robots in architecture schools has proliferated during the last decade, leading to a large variety of small and medium scale structures featuring automated processes in design and construction. However, the use of these processes has mainly focused on the pure automation of human actions, establishing workflows mostly based on the post rationalisation of continuous topologies. Many of those examples are based on a proto-parametric approach (Schumacher, 2016), in which parts are intrinsically adjustable and continuously differentiated.

The work in this article questions the acceptance of a continuous paradigm within robotic fabrication. It instead proposes a model based on a discreteness, in which building elements combine together into larger assemblies, rather than being described from the rationalisation of a whole. This argument is based on both the questioning of the "digital" in architecture and technical concerns in the search of a new design model within automation.

Gerschenfeld, Carney, Jenett, Calisch, and Wilson (2015) argue that digital fabrication is caught in a permanent conflict between complexity and speed and that it can only achieve both if it becomes discrete and "digital." They go on to say that a process or operation can only be considered digital if it operates on a material that itself is digital. Otherwise, we are still in an analogue process.

Digital data is based on a discrete, discontinuous representation of information, whereas analogue data is intrinsically linked to continuous differentiation. We can argue that extruding or weaving material guided by an industrial robot is, therefore, the physical representation of an analogue process. This leads to the possible emergence of fabrication errors within the manufacturing process which require specific solutions that generally follow irregular patterns. A purely "digital" process would feature a discrete number of building elements and connection possibilities, leading to a limited set of information that would ease the creation of automated workflows.

The research presented in this article focuses on the design methods based on discreteness that aim to establish the frameworks for a purely "digital" architecture from design to fabrication. This approach leads to a series of projects in which building blocks are conceived for their robotic assembly into a large variety of structures. These projects are developed in a research-through-teaching context in the Bartlett Architectural Design (AD) Research Cluster 4 (RC4). AD is a part of BPro, an umbrella of post-graduate programmes in architecture at the Bartlett School of Architecture at University College London. The research, started in 2013, is led by Manuel Jiménez García, Gilles Retsin, and Vicente Soler. The student work is set within the framework of Design Computation Lab, which the three authors co-direct with Mollie Claypool.

Projects

INT

INT (Zoey Hwee Ting Tan, Xiaolin Yin, Qianyi Li, and Claudia Tanskanen, 2016) uses a discrete approach to introduce complexity in prefabrication. The team proposes timber blocks as basic building elements which could be robotically assembled into large-scale structures. An industrial robot is equipped with a gripper which could pick and place these elements into place. The geometry of the blocks is defined by the slots needed for gripping these elements in order to differentiate the combinatorial process. The application is based on a button-up approach, in which a flexible number of identical elements of two different scales combine together to fill a given volume. In the first stage, this 'basic mass' is analysed with Finite Element Analysis performed in Grasshopper Karamba. When imported into the framework, the force-flow and stress values influence the rotation of the pieces, limiting the possible connection to the satisfactory level of surface area between pieces. In the areas of a design that require more strength, the ratio of blocks with high surface area overlap is much larger. Blocks can be added or deleted according to variables such as cost or assembly time.
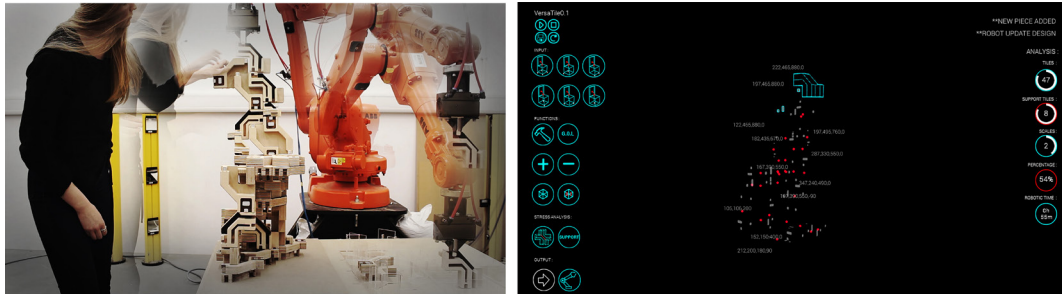

FIGURE 1 Interaction with the robot: The entire system can be recalibrate itself when elements are added or deleted either physically or digitally.

The blocks are equipped with integrated markers. These are read by an OptiTrack system that creates a digital version of each block in a virtual space. This setup facilitates the real-time update of the digital model while the assembly process takes place. This parallel between the digital and physical realm leads to a more direct interaction with robots since the entire system can recalibrate itself when elements are added or deleted either physically or digitally. To further ease the correction of errors while the assembly process takes place, this feature also allows the introduction of design changes at any given time.

The combinatorial algorithm used for this project allows the creation of infinite variations of structures. To prove the viability of the workflow, two chairs and one prototypical column were robotically fabricated. The chairs show two different degrees of human involvement in the design process. The first one is algorithmically created without human input, purely based on optimisation, while the second prototype is authored by the students and shows different pattern combinations with a symmetrical bias and a 2.3m column prototype, which aims to address architectural and structural requirements on a larger scale. Although the combinatorial algorithm and the pick and place system proved to be successful, the connectivity between the building blocks could be further improved to allow not only the assembly of these structures, but also their reconfigurability.

Transfoamer

Transfoamer (Gefan Shao, Na Wei, Ran Chen, and Zhilin Chen, 2017) builds on Design Computation Lab's research on Discrete Robotic Assembly, introducing the utilisation of lightweight materials to ease the fabrication of larger structures. The project aims to achieve high efficiency in robotic manufacturing by automating both the creation of the building blocks and their assembly.

A large block of high-density polystyrene foam is transformed into discrete blocks by an industrial ABB robot equipped with a custom-made hot-wire cutting end-effector. The building block is based on a tetrahedral grid, which allows an efficient packing of pieces in each polystyrene block to reduce material waste. Each building element is cut in three minutes, and later coated with polyurea, an elastomer derived from the reaction between an isocyanate and a synthetic resin-blend component through step-growth polymerisation. This increases the tensile strength of the pieces, as well as offering abrasion resistance and waterproofing. The coating also acts as a fire retardant.
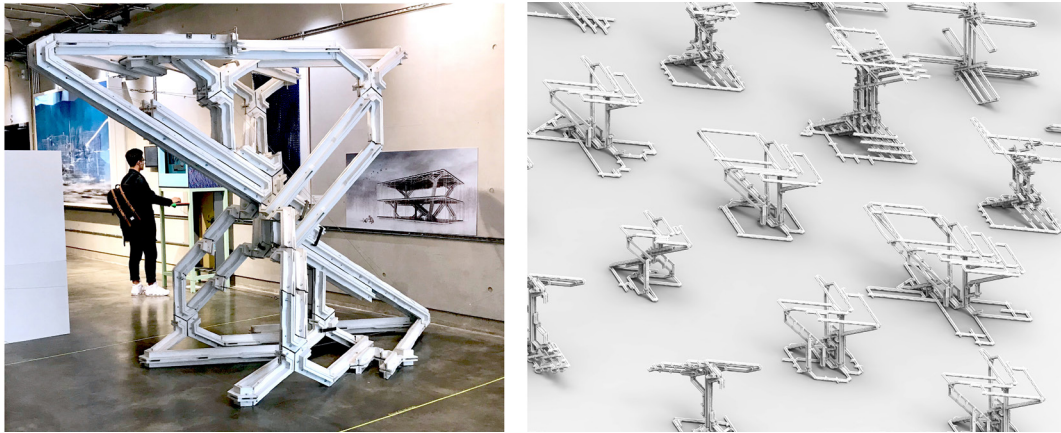

FIGURE 2 Combinatorial rules define number of rotations of the elements and respond to fabrication constraints and structural requirements.

In a subsequent step, an industrial robot assembles the blocks into larger chunks through the use of a vacuum gripper designed specifically for the geometry of the building elements. This process could also be produced by multiple robots working in tandem to reduce building time. The students developed an application using Unity that incorporates a computational logic to generate multiple design interactions. A set of combinatorial rules is applied to define a limited number of rotations of the elements and responds to fabrication constraints and structural requirements. For every possible combination, a probability factor is computed by relaxing the discrete optimisation problem into a continuous optimisation. Two topological methods – BESO (bidirectional evolutionary structural optimisation) and SIMO (solid isotropic microstructure with penalisation) – establish the guidelines driving the geometrical composition in the emergent structure.

The students produced a 3m x 3m x 3m prototype at the conclusion of this project, including 83 short tiles and 69 long ones. As in the INT project, an elongated component is added to the discrete set of pieces that allows spanning between structural nodes created by the smaller size pieces, as well as creating cantilevers.

Roblox

Roblox (Anna Uborevich-Borovskaya, Chenghan Yu, Hungda Chien, and Yen-Fen Huang, 2017) explores the use of combinatorial algorithms and robotic assembly at the scale of the built environment. The project is based on standardised UHPC (Ultra-High-Performance Concrete) building elements which can be assembled into large scale structures. They can be later disassembled and subsequently reconfigured into different formations, thus enabling flexibility and adaptability in construction that is missing from traditional prefabricated systems.

The team developed a building block which, as in the INT project, relates its shape to the grip of an industrial robot. The geometrical constraints to allow casting by using a laser-cut plywood reusable mould as well contribute to the formal definition of the building element. The initial element is generated from 7 regular triangles, connected into an L-shaped block. Its long side can be modularly extended into four different lengths. This allows the reduction of bending moments in those connections requiring structural continuity.
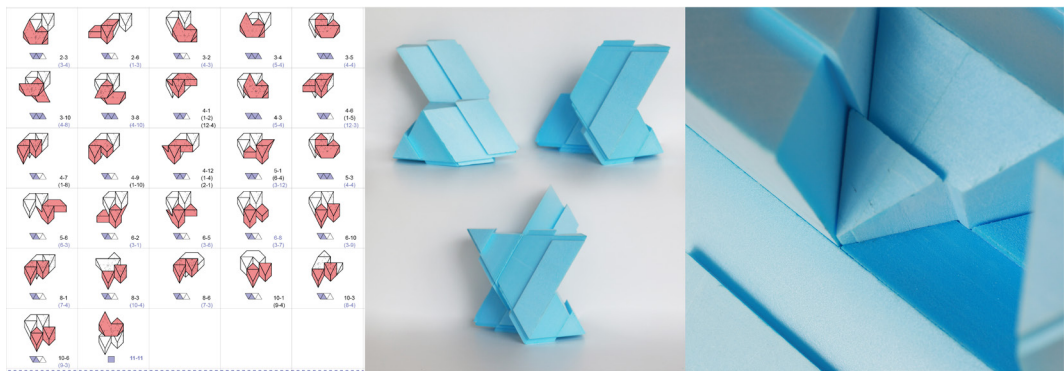

FIGURE 3 Combinatorial process generating stable structures.

To introduce reversibility in the assembly, the pieces are connected mechanically through triangular steel joints. As in other RC4 projects such as Transfoamer, the students built a custom application based on Unity which drives the combinatorial process towards stable structures. This software uses spatial rules and structural analysis as the main drivers for the combinatorial algorithm, calculating the type, position, and rotation of each piece in response to the main directions of stress, as well as ensuring the emergence of circulations and habitable space within the structure.

A plethora of pavilion-scale structures were created using this software. Under the sponsorship of LafargeHolcim, one of these structures was physically prototyped to demonstrate the viability of the system in construction. Rather than a closed shape, the built formation represents an open-ended construction system which could be extended into larger structures. The students digitally tested its potential, generating a 2-storey 14m x 8m x 7m housing prototype, not only using the UHPC blocks for the structural frame, but also extending the discrete design methods for the floor tiles and façade elements that feature clipping panels for their robotic assembly.

FIGURE 4 Physical prototype to demonstrate the viability of the system in construction.

Conclusions and Future Work

The projects featured in this paper demonstrate the potential of Discrete Robotic Assembly in architecture. Although it is still in its early stages, this research proves that there is an increase in construction efficiency in a discrete design framework. The research shows how a limited set of assembly possibilities eases the automation of the manufacturing process and leads to a reduction of labour, construction time, and cost. This intrinsic link between discrete design methods and automation hints at a potential shift in the construction industry governed by a new paradigm in computational design, where architectural elements are defined from and for automation.

RC4 research evolves more tectonically efficient methods in design and automation. While INT and Transfoamer focus primarily on the creation of different workflows in robotic fabrication, Roblox acknowledges the introduction of other architectural systems such as curtain walls and flooring. This demonstrates Design Computation Lab's research direction towards optimising construction through algorithmic design and fabrication.

The future development of this research includes a further investigation on hybrid systems that interface different materials with different tectonic purposes. In parallel, the lab aims to refine the models of interaction with robots in order to create not only a more economical and optimised construction framework through automation, but also to offer architectural values previously unexplored.

Acknowledgements

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Structural Adaptation through Stiffness Tuning

Arwin Hidding [1]**, Henriette Bier** [1]**, Qinyu Wang** [2]**, Patrick Teuffel** [2]**,
Gennaro Senatore** [3]**,**

[1]   *Faculty of Architecture and the Built Environment*
        Delft University of Technology
[2]   *Faculty of the Built Environment*
        Eindhoven University of Technology
[3]   *Applied Computing and Mechanics Laboratory*
        École Polytechnique Fédérale de Lausanne

Abstract

Adaptive design strategies have been employed to improve structural performances in terms of load-bearing efficiency and energetic impact as well as to achieve multi-functionality. In this work, we investigate a passive adaptation strategy that employs variable stiffness in robotically printed materials. This paper focuses on the design and robotic fabrication of a chaise longue that can change shape to function as both recliner and chair depending on user requirements. The approach is unique in the way computational design is linked with robotic production. In this context, the design of the chaise longue is not limited to a formal process, but extends to the synthesis of the material distribution layout in order to achieve the intended functional behaviour.

Keywords

structural adaptation, adaptive design strategies, robotic printing

Introduction

Most engineering structures and products are overengineered as a result of being designed to meet strength and rigidity requirements to withstand worst-case loading scenarios which, in practice, occur very rarely. The conventional approach to cope with these requirements not only creates significant material waste, but also restrains structural and architectural design. Instead, structures could employ adaptation through controlled shape changes in order to counteract the effect of loads (e.g. stress, deformation) and achieve multi-functionality.

Previous work has shown that state-of-the-art adaptive design strategies can be employed to lower the environmental impact of structures while achieving a higher level of structural efficiency, e.g. to increase the height of tall buildings as well as the span of bridges and self-supporting roof systems (Teuffel, 2004; Senatore, Duffour, Hanna, Labbe, & Winslow, 2011; Senatore, Duffour, Winslow, & Wise, 2018; Senatore, GDuffour, & Winslow, 2018). Adaptive design strategies in combination with additive manufacturing at high spatial resolution (micro-scale) have been implemented to synthesise products with specific material behaviour, for instance for orthotropic foams (Martinez, Song, Dumas, & Lefebre, 2016; 2017). However, in practice, the application of these techniques is still limited.

In this work, a passive adaptation strategy, which employs variable stiffness in robotically printed materials, is investigated. This work focuses on the design and fabrication of a chaise longue that changes shape as a result of deformations induced by the weight of a user as shown in Fig. 1. The shape change is designed to accommodate both seating and a near-supine position for sleeping. The design of the required structural adaptation is implemented by tuning material stiffness through material pattern differentiation.
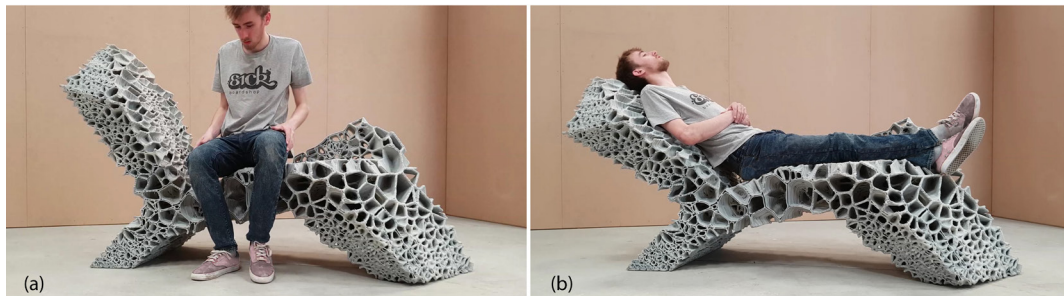

FIGURE 1 Chaise longue shape change from (a) sitting to (b) lying down obtained by tuning the stiffness through material deposition.

The chaise longue is made of thermoplastic polymer (TPE), which can stretch significantly (300% under 2.4 MPa) and revert to the original shape. The material's internal arrangement is based on a cellular pattern that is employed to create a self-supporting structure and can be fabricated by a robotic arm. By using robotic additive manufacturing that deposits fused material using a Stäubli TX200 6-axis robotic arm, the chaise longue was produced within 30 hours. A demonstration movie of the fabrication process is available online (Bier, H., Hidding, A., Wang, Q., Teuffel, P., & Senatore, 2017). The process is based on Design-to-Robotic-Production (D2RP) techniques developed at Delft University of Technology (TUD) (Bier, Liu Cheng, Mostafavi, Anton, & Bodea, 2018; Bier, 2018; Bier, Mostafavi, Anton, & Bodea, 2017) for additive and subtractive manufacturing. It is unique due to the integration of functional, structural, material and production requirements in design.

Design Process

The design process described in this section has been developed during a research project carried out in 2017 through support of 4TU Federation (Wang, Senatore, Teuffel, Hidding, & Bier, 2018).

The chaise longue is designed to accommodate an average human body either sitting or lying. A virtual human body model has been used to define the boundary geometry of the chaise. The desired shape-change from sitting to lying has been achieved by tuning the stiffness through strategic material deposition. This approach is not commonly used in additive manufacturing because material is usually uniformly deposited. The main requirement is for the chaise longue to be self- supporting. In addition, it should be 3D-printed without any supporting material.
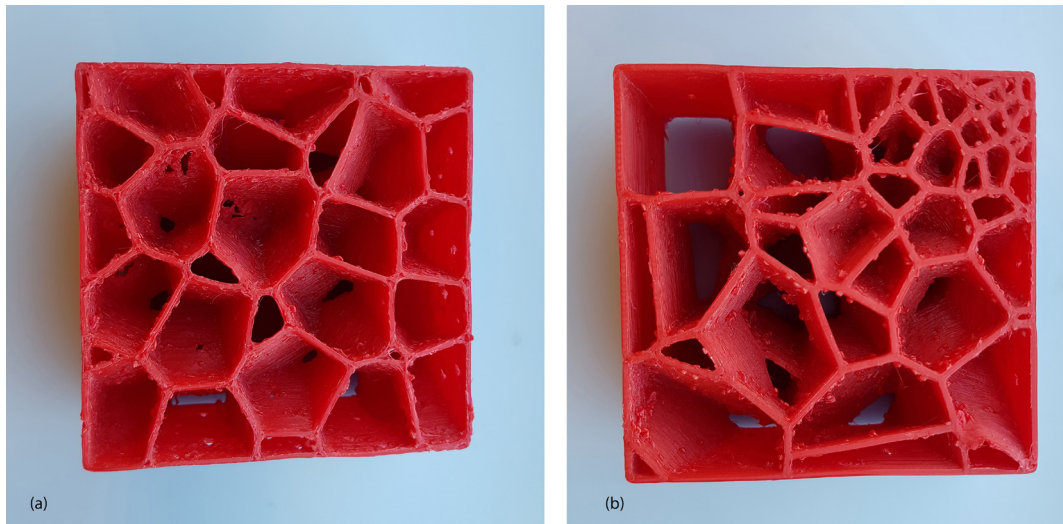

FIGURE 2 Uniform density distribution (a) and transition from small to large cells (b).

The cellular pattern is made of units, of which dimensions are varied to obtain variable stiffness properties. Several patterns have been tested to characterise deformation behaviour and fabrication feasibility. The aim is to obtain a large deformation of the back support when a user lies against it as shown in Fig. 1 (b) yet maintain structural integrity. To achieve this required deformation behaviour, cells are differentiated by varying their size distribution along specific directions as shown in Fig. 2 (b) as well as the cell height in the out-of-plane direction. The combination of these geometrical variations results in relatively well-defined directional stiffness properties of the assembly, which has been employed to obtain the required functional behaviour of the chaise longue.

Variable stiffness properties though geometry and material deposition

Material deposition is driven by stress: material density is increased where high stress areas occur whereas porosity is increased where low stress areas occur. The external load is modelled as a distributed load equivalent to the average human weight (80 kg), sitting or lying on the chaise longue. As a result of the structural analysis, the principal stresses are derived. The lines indicate tension (red) and compression (blue) stresses.

Fig. 3 (a) shows a detail of the chaise including the corresponding stress lines. The stress lines are subdivided to be converted into a point cloud by extracting points along their segments. The point cloud density is related to the stress intensity and thus more points are distributed in highly stressed area. These points are used to generate a Voronoi pattern (Fig. 3 b). The position of the points determines the position and sizes of the cells, as well as the angles of the cell walls. When the points are packed more densely, the 3D cells become smaller, since the cell size is influenced by the positions of neighbouring points. Therefore, size and density distribution of the cells can be controlled by adjusting the placement of these points. This way the cells are set to be smaller in highly stressed area increasing material density though their walls (Fig. 3 c). Fig. 3 (d) shows a detail of the 3D-printed cells.

Regarding the back support of the chaise, the combination and transition between high- and low-density areas ensure enough resistance to counteract bending and torsion caused by the weight of the user, while allowing for large deformations to fulfil functional requirements. The cell shapes and sizes, as well as the overall shape of the geometry can be adapted to individual requirements. For example, depending on the user's weight, the cell densities can be adjusted to match individual needs. This process has been implemented through parametric modelling using Rhinoceros 3D and its built-in visual programming environment Grasshopper with the structural analysis plug-in Karamba.
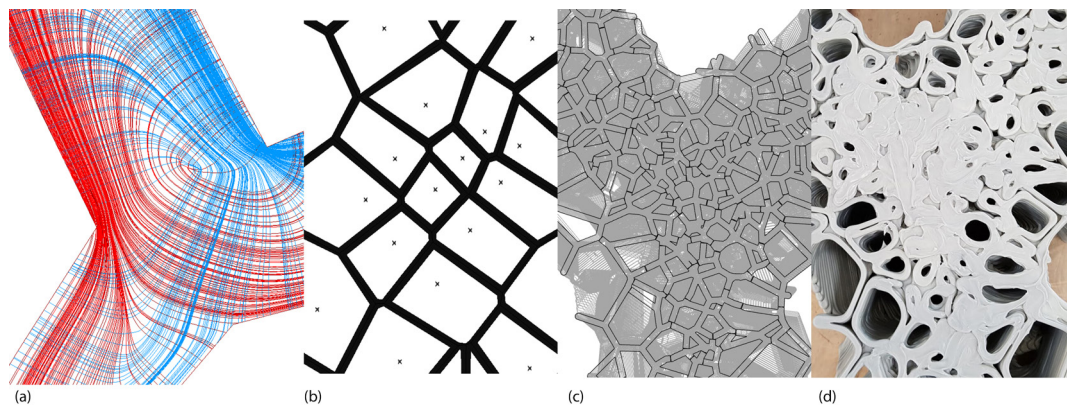

(a)　　　　　　　　(b)　　　　　　　　(c)　　　　　　　　(d)

FIGURE 3　Stress analysis detail (a), subdivision pattern (b), cell face section (c), cell face section printed (d).

Robotic Production

Cell Size and Thickness

The cell walls consist of two layers in order to increase stability during material deposition. Thermoplastic polymer (TPE) remains malleable after extrusion and therefore deforms significantly when unsupported. These material characteristics prevented the use of wireframe structures, as implemented in the work of Martínez [6]. For this reason, a cellular approach via continuous self- supporting material deposition has been developed.

The angles of the Voronoi cell walls are also controlled by strategic placement of the cell centres. These points are placed in a configuration so that all cell walls are oriented between -45Ð and 45Ð in relation to the printing bed to avoid the need for any additional supporting material during material deposition.

Conversion of the cellular pattern into robotic toolpaths is a process that starts by intersecting the assembly though planes as shown in Fig. 4. The intersection results into a series of polylines, specifically one polyline for each cell (Fig. 4 a). Since it is more efficient to deposit material via continuous tool paths, an algorithm has been developed to join the individual polylines into one continuous line (Fig. 4 b). By using this algorithm, which is based on an implementation of the traveling salesman algorithm, fabrication time decreased by 90% through minimisation of the printer head travel time between material deposition.
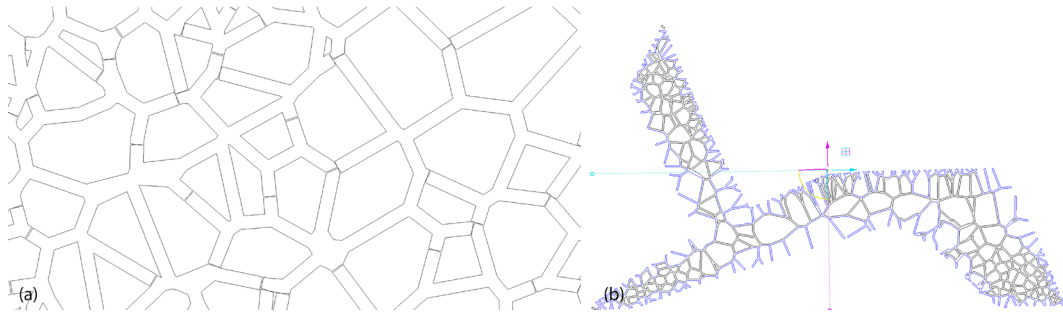

FIGURE 4 Conversion of cellular geometry (a) into robotic toolpaths (b).

Polylines to G-code

The X, Y, and Z coordinates of the control points of the polylines are converted into G-code using a proprietary algorithm. The link between the cellular pattern, their control points, and the resulting G-code ensure satisfactory control over the production process which was completed without any manual intervention.

Conclusion

The Design-to-Robotic-Production (D2RP) process presented in this paper is unique in the way it links computational design with robotic production. Along with traditional design tasks, this process involves the design and optimisation of material distribution layout to achieve desired functionalities. This approach introduces an adaptive behaviour that allows for customisation as well as improved performances (e.g. increased comfort for the chaise longue case study). It furthermore reduces material waste by depositing self-supporting material only where structurally required, while speed of material deposition is increased because of the proposed optimised robotic path.

This D2RP process has potential for developing other types of products including civil engineering scale structures and components. Future work will investigate scaling effects by modelling and testing larger scale prototypes. Furthermore, the potential of stiffness control to improve comfort and durability of industrial design products by cushioning and damping will be explored.

Acknowledgements

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Interview

Dialogs on Architecture

Henriette Bier [1], Keith Green [2]

[1]   *Faculty of Architecture and the Built Environment*
Delft University of Technology

[2]   *College of Human Ecology*
Cornell University

Abstract

Dialogs on Architecture is a series of dialogs between researchers and practitioners who are embracing the intellectual model of high technology and are involved in its advancement and application in architecture. The first dialog focuses on the impact of an intellectual model of high technology on architecture, and takes place between Henriette Bier (HB) and Keith Green (KG).

Keywords

high technology, machine age thinking, cyber-physical systems

Dialog #1: The impact of the intellectual model of high technology on architecture

Considering the impact of the second industrial revolution on modernist architecture, the question of how the third and fourth industrial revolutions influenced architectural thinking and practice needs reconsideration.

If the second industrial revolution, which involved inter al. mass production, assembly lines, and electricity, influenced modernism with its Machine Age thinking, transforming buildings into machines for living, the third and the fourth, which involved computation, automation, and cyber-physical systems, implied that the Digital Revolution ended the intellectual model of the Machine Age founded in the mechanical and moved towards a new model of high technology, the question of how this new model influences architecture is the focus of this dialog.

HB: If Le Corbusier acknowledged that architecture was lost in the past, engineers at the time were embracing new technologies and were building simple, effective structures that served their purposes. He noted that the spirit of the Machine Age had begun to produce works that embodied its principles. This implied radically simplified forms according to rational and functional requirements, and mass-produced standardised building components.

I would argue that we are today, again, lost in the past. And while other industries advance the intellectual model of high technology, the building industry is slow to pick up developments, and contemporary architecture remains fundamentally conventional and lacking of innovation. The role of the architect is reduced to a service provider, collaging buildings from various parts designed and produced by other parties.

FIGURE 1 Human-robot collaboration during staking of linear components (© RB).

KG: You're a harsh judge of architecture practice today, but I agree with your assessment, which probably makes us not so welcome to our own kind.

But I would even go so far as to say that architects today are not lost in the past, but simply lost. Being lost is not new to architecture; we were lost (for one) in the later 1980s and early 1990s, caught in the middle of post-modern capriciousness ("Po-Mo"–where a little bit of the past, on the cheap, was skim-coated onto building facades), it's bedfellow "New Urbanism," a new formalism canonised by Philip

Johnson's "deconstructivist" exhibition at MoMA, and strangely, a revival of classical architecture. On top of that, opportunities for architects to build were few in a global recession. But being lost at this earlier time was not without reflection, pondering, and intensive, critical thinking and making; in other words, being lost then was productive for architecture. Lamentably, architecture today no longer embraces this disorientation as a means to propel it; instead, architecture today babbles shards and fragments of the past without any objective or strivings (if, as Rossi and Tafuri argued back then, objective is too strong a word for architecture). There seems to be little at stake for architecture today, apart for gaining notoriety and being cool. Notoriety and being cool isn't bad – architects have long thrived on it – but is that all that's left for us today?

HB: I believe that's not what's left for us today. Advancements in robotics, cyber-physical systems, etc. bring about the opportunity for architects to reinvent themselves. Robotic production empowers architects to become master builders, and robotic operation challenges them to envision buildings as interactive environments. However, architectural practices and the building industry are slow in engaging with these technologies. Considering that automation has been successfully implemented by other industries for decades now, how is it possible that the building industry still adheres not to high but to low technology principles?

KG: Building practices, building construction management, and the organisation of the building construction business are entrenched in the past. There is not sufficient incentive to change. Meanwhile—and here is the good news about architecture today—a small segment of the architectural community is thankfully developing new building materials, new building systems, new ways of building with machines, and embedding new technologies into buildings that make them smarter and more sustainable. But the bridge between these innovations and their implementation in the building industry is a tenuous line seldom crossed. Higher profile architecture commissions can make the journey, bringing their architects notoriety and that cool factor (sought after or gratefully welcomed). Perhaps we have to rely on national and local government building codes to compel the use of such innovations. The future of the planet and the society that inhabits it rely partly on designing and building innovatively. It's paramount.

HB: If the building industry would be willing to apply the intellectual model of high technology, the integration of computation, automation, and cyber-physical systems in design-to-production processes would need to be on their agenda.

KG: Maybe the building industry will not be first in the application of high technology in the design-to-production process. The manufacturers of appliances, industrial machines, and hardware are perhaps better prepared to prefabricate, mass-produce, and mass-customise buildings. It's difficult to think through the extraordinary ramifications of this paradigm shift in the building industry on the built environment, workers, and the business of building, but I think this future trajectory is inevitable. This likely means architects will have to become, far-more so, something other than the cottage industry that we've long been. Designers of a different ilk –industrial designers, interaction designers, and information designers – may be better prepared for the challenge.

HB: What then are the implications of this shift on architectural education?

KG: I think we have architectural education all wrong today. Along with today's architectural practice and the building industry, architectural education is lost, in my judgement. The biggest shortcoming of architectural education is its isolation. Sure, there are a few remarkable efforts by architectural educators to connect architectural education and architectural research within the schools to other disciplines across the campus for the mutual advances of architecture and these other concerns. But overall, architecture seems absurdly stuck in that romantic, atelier-Beaux Arts model: the architecture studio filled with architecture

students overseen by the architecture master. (Once in a while, maybe a collaboration occurs with landscape architecture or, god willing, planning or urban design.) From this, there is little of substance generated that speaks to those potential collaborators from other parts of the academy: scientists and engineers and humanities scholars investigating digital technology, materials, biological systems, the environment, the mind and the body, society, policy. Too many architecture schools continue to cultivate in our young people an architect's propensity for naval gazing and narcissism, and it's not getting too many of us anywhere.

On the topic of training architecture students, I have yet to find an architect that can characterise the objective better then Violet Le Duc, who offered (as a critique of the Beaux Arts) that we should "train their young minds to reason and to become aware of all their deficiencies, instead of exciting their youthful vanity." Architecture schools do a lot today to excite youthful vanity at the neglect of challenging students intellectually, pondering the limitations and opportunities of architecture, expanding the skill set well beyond traditional limits, and expanding students' vision to the vastness of designing a future for this planet which demands that architects work intimately with fellow collaborators from not just the usual trades (that we've commandeered over the centuries) but from so many other disciplines relevant to and prepared for the challenges and opportunities of living today. Around the globe, we have real challenges and real opportunities where architecture can make a difference, but we're only opening the door a little bit to these fantastic possibilities for the future. Opening the door a little bit is perceived to be safe, protective of the way architects do and have long done things, but I think this cowardice or resistance to change may be the death of architecture outside a very narrow band of elite, boutique practices that can persist in the old vocation of architecture. Have we already arrived at this finality?

FIGURE 2 Interactive, portable learning tool for children enhancing personal and computational expression, and particularly, playful storytelling (© Architectural Robotics Lab).

HB: If such resistance to change may be somewhat understandable when it comes to practices, it is unclear why academia, where change is supposed to happen, is resisting. While several academic groups are working on these topics, compared to the resisting majority, they represent a very small percentage that even, after a decade, is still operating as avant-garde.

Considering that responsive architecture had already been introduced by Nicholas Negroponte in the 1960s, as the result of the integration of computing power into the built environment, we look back at a history of more than a half-century. In the 2000s, new works of responsive architecture have emerged such as dECOi's Aegis Hypo-Surface acting as a programmable skin, and NOX's Freshwater Pavilion containing a programmable audio–visual interior. Later, MIT's Kinetic Design Group has been developing intelligent kinetic systems which re-configure to meet changing needs, while the Interactive Architecture Lab at Bartlett has been constructing interactive installations that are integrating robotics, material science, and computational technologies.

In the last decade, robotics have been increasingly employed not only for activating building components but also for producing them. In particular, ETHZ and Bartlett have been active in developing robotic production techniques. Ourselves at TUD and you at Cornell have been also contributing to advancing robotics integrated into building processes and buildings. However, the knowledge transfer from academic environment to industry remains rather slow.

KG: You and I, and the peers you reference, stand outside the current practice and the academy. Why?

On one hand, I think that architectural production still demands, as Vitruvius saw it two thousand plus years ago, that an architect that knows a little bit about a lot of things. Making architecture is complicated, and so it requires wide-ranging competencies. I don't view this cardinal trait of the architect "knowing a little about a lot" as being at all a bad thing; quite the contrary, I think; rather, that it's a marvelous aspiration: the architect as a culivated Renaissance figure. But this character of knowing a little bit about a lot is also against the grain of today's world that requires, increasingly, also, specialisation. And I don't think specialisation—an intensive, singular focus—is the "strong card" of the architect. Moreover, I wonder whether the architect of today is really as cultivated as the architect of just twenty years ago, when architects were maybe poorer financially but richer in thinking and engagement—of the arts, of design, of philosophy and critical thought. With greater professional opportunity (in better economic times) came a diminishing intellectual engagement. Sadly, I don't see students or younger faculty members as interested in a lot of things that the previous generation embraced.

On the other hand, I'm fearful that, in architecture today, we are witnessing a new conformism. Through history, architects have been beholden to the likes of Popes, Kings, Dictators, and Nobles who were able to pay for works of architecture. This is unchanged. But recently, there seems to me an odd twist to these relations: architects (given the opportunity) create singular works to feed the hunger of a few, very empowered people, and the result is a stream of novel additions to the built environment that don't have much more to say to us, or about us, than "look at me." It's a march of the same novelty, which is tiring. In the past, maybe architecture reflected some yearnings of society. Today, we have architecture-as-trophies, awarding their owners for winning (?) the game. The new conformity in architecture is in pleasing the winners with yet another architectural icon materialised to honour their achievement. And the academy is oddly complicit with architectural practice in this tendency. Why? A lack of imagination? An intellectutal fatigue? The seduction of digital means? An addiction to social media?

HB: So where are we – you and I and the others I mentioned – in all this?

KG: Clearly outside. And misunderstood. We are architects who were taught to know a little bit about a lot. We are still curious. And, at the same time, we are specialised. It's no small achievement – to be architects that know a little bit about a lot, to be curious, to be also specialised – but it situates us as a threat to the status quo of the moment, or perhaps it situates us such that we can be ignored by the architectural current—an indomitable force. But I think what our little, loose thread collective is striving for (not discounting others like us that we do not yet know) is forging an inevitable future in which buildings, significant or more solemn, are increasingly the products of manufacturers and design entities and means of production that are not the mainstay of today's architectural practice and the academy.

On perhaps a related subject, the architectural profession continues to be predominately male, despite gains by women in numbers of students entering the schools. Do you think, perhaps, we might find hope for the future of the profession in women leaders? Like so much of the cultural and media world, Architecture is having its #MeToo moment with Richard Meier's disgrace and the circulation of the Shitty Architecture Men list. Do you have a sense that perhaps a new geneariton of female architects can resist the trappings of the architect-client relationship and forge a path to self-growth and architectural exploration? And, finally, what do you envision the small group of cohorts, and others like us, might do to maintain or advance the same. Your final words concerning this glimmer of a prospect might be an optimistic ending to our conversation, at least for now.

HB: When it comes to women leadership and gender balance in academia, there is still room for improvement. For instance, the TU Delft Feminists legitimately complain about the imbalance between student and professor female representation. How a more balanced gender representation would change the profession and how the small group of cohorts, and others like us, might advance it is still unclear; but to quote the TU Delft Feminists it is clear that "We need to learn not to centre whiteness, heterosexuality and masculinity as the default human body and experience, as we now almost universally do. We need to challenge assumptions about superiority based on old, neo-colonial narratives that allowed a few to dominate many. In this way, we can stop reproducing discrimination and oppression of 'others' without even noticing what we are doing. Through education we have an opportunity to transcend binary and essentialist thinking to become infinitely more nuanced and sublime as professionals, and as human beings. We can't design and think effectively about the complexity of the built environment without this richness at heart. Why condemn another generation to standards that don't fit, technologies that won't sustain, and practices that exclude far too many?"

KG: You offer many compelling thoughts and questions here that I embrace and ponder. I look forward to our continuing conversation, which dates back many years. I hope it continues for many years to come.

SPOOL