Robotic Building

Edition DETAIL

Architecture in the Age of Automation

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Foreword
The Age of Computational Brutalism
by Mario Carpo

To all who, like me, became architects in the last quarter of the 20th century, modernism was the defining moment in the history of world architecture: the one point in time when the design professions rose up to the task of shaping the totality of the built environment, in full awareness of the technical and economic constraints, of the political nature, and – a bit later – also of the natural limits, of all design and building. Not surprisingly, for that very reason some saw modernism as the zenith, others as the nadir, of design history. Yet, in purely conceptual terms, the main achievement of the masters of modernist design was in fact a fairly modest one: they just collectively decided – and none too soon – that architecture should come to terms with the technical logic of mechanical mass production. That, in turn, was never rocket science; now, as then, everyone can find its basics explained in any first-year economics primer. Most mechanical technologies of mass production are matrix based and use mechanical matrices (moulds, casts, dies or stamps) to print out identical copies. As matrices cost money, it makes sense to try to use them many times over, to amortise their cost by spreading it over as many identical copies as possible. This is how the reproduction of standardised, identical copies generates economies of scale: the more identical copies we make, the cheaper each copy will be.

Today we know that digital fabrication technologies no longer work that way: in so far as most digital production tools, either subtractive or additive, are not matrix based, the digital reproduction of identical copies does not generate any economies of scale: there is no need to reuse any mechanical matrix when there is none to begin with. When digitally made, any copy is a new original and making more of the same will not make any of them cheaper. This is what we call mass customisation: one of the most revolutionary ideas that architects ever came up with; one that will change – and has already deeply changed – the world in which we live.

And that is already history – a history that started almost one generation ago. Above and beyond that, however, for the last ten years or so a new crop of digitally intelligent designers could not fail to notice that more and more powerful computers are now increasingly taking on a number of “intelligent”, problem-solving tasks. Much as in the 90s computers were primarily seen as tools for making (tools for making architectural drawings and tools for making physical objects), today computers are again being hailed as tools for thinking – in a sense, going back to what computers were meant to be when they were invented and called “electronic brains” (and not “electronic hands”, for example: that came later). Indeed, Artificial Intelligence was already a very hot topic from 1956 (when the term was minted) to the late 1970s, when both the term and the research relating to it were forgone and ditched. Unlike its hapless predecessor, however, today’s AI often seems to work, sometimes even surprisingly well, and in architectural design this revival of the computer as a thinking machine has been the springboard for what we now call the second digital turn, based on discretisation, excessive resolution and particlization – the visual display of logics of notation, calculation and fabrication beyond the scope and compass of human understanding.

This important, ground-breaking book is about the merger of new computational tools for making and thinking in a new architectural paradigm, which the authors call automation. The term is felicitous and aptly chosen. First generation tools for digital manufacturing were mostly subtractive and second generation mostly additive. Today, the most versatile tool for computer-driven making is the robot, generally seen as a versatile device for carrying out physical tasks, hence the ideal bodily extension, so to speak, for an electronic mind that is now capable of making independent, intelligent choices. However, as nobody has yet produced any workable definition, let alone taxonomy, of either robotics or Artificial Intelligence, the authors of this book have very reasonably chosen to avoid sci-fi diversions and ontological traps, keeping instead to the oldie but goodie notion of automation. A cuckoo clock can keep the time automatically (intellectual problem-solving independent from human intervention: that’s AI), and equally automatically perform a set of mechanical operations in physical space as the means to an assigned end (in this instance, telling the time: that’s robotics). But computational automation of making and computational automation of thinking can now be synced, as never before. This is the conceptual novelty highlighted and advocated in this book and illustrated by many of the cases presented here.

And this is how it works. When architects first started experimenting with digital mass customisation, in the late 90s, they had to fit that novel idea to some contingent, but drastic technical limits in the materials they could use and in the sizes of the pieces they could produce. In Greg Lynn’s seminal Alessi Teapots, a non-standard series of 99 variations of the same parametric model, each of the 99 teapots looked like, and was meant to be seen as a monolith – a single metal block: that was not the case, but it was nonetheless the idea the series was meant to convey, and this is how each teapot would have been fabricated, if titanium sheets could have been milled, 3D printed or extruded. However, when trying to apply the same logic to a non-standard series of actual buildings (the Embryologic Houses, circa 1998–2000), Lynn was the first to point out that those fabrication processes would not easily scale up. The shell of a parametric, non-standard house could be made of a vast number of digitally mass-customised, non-standard panels, but these in turn should be fastened to a structural frame and to each other; the frame itself, due to its irregular form, would have to be laboriously hand-crafted and so would each fastening nut and bolt and junction and joint between the parts. In short, twenty years ago Lynn's non-standard house would have ended up being more hand-made than digitally fabricated.

The transfer of non-standard technologies from the small scale of product fabrication to the large scale of building and construction remains to this day a major design issue. Some digital makers have tried to duck the issue by enlarging the size of their printers (and examples of these technologies are featured in this book); but as printing machines tend to be bigger than the objects they print, this has resulted in a number of quixotic experiments with rather unwieldy hardware. Today, the versatility of robotic machinery leveraged by the brute force of big data computation suggests a different approach: instead of printing bigger and bigger monoliths, it may conceivably be easier to start with any number of parts, as many and as small as needed, leaving to AI and robots the task of sorting them out and putting them together. Today, thanks to AI, an almost unlimited number of different (or identical) parts can be individually notated, calculated and fabricated; and, also thanks to AI, an almost unlimited number of different (or identical) robotic gestures and movements can be scripted and executed for their assembly. The technical logic of digital mass customisation (the mass production of individual variations at the same unit cost of mass-produced identical ones) is perfectly mirrored by the technical logic of AI-driven robotic assembly: identically repeated robotic gestures cost the same as variable ones; robotic operations of similar amplitude or duration will cost the same whether the actual robotic movements are the same or not.

In fact, as both fabrication and assembly can be standardised (making identical copies or identical gestures, respectively) or non-standard (making variable copies or variable gestures, respectively), the diligent reader is invited to compile the mathematical matrix of the four resulting modes of combined production and assembly – of which one, the standard assembly of non-standard parts, appears improbable; the remaining three describe most of the examples discussed in this book. Should an even more diligent reader feel inclined to build a bigger matrix, one may add that standard fabrication, non-standard fabrication, standard assembly and non-standard assembly, can all be delivered by dint of manual, mechanical and digital processes (at least in theory, but with the exception of non-standard production and assembly, which can only be achieved manually or digitally). This bigger matrix could in turn apply to the quasi totality of architectural history.

Given this bigger picture, the authors' noted and distinctive predilection for the non-standard assembly of standardised parts (which, at the time of writing, is the marquee of the Bartlett school of computational brutalism) may appear quirky and arbitrary. Assuredly, if new technologies today exist that allow us to mass-customise any assembly of parts, why should similar – indeed, often older and more established – technologies not be used to mass-customise the parts themselves? As the authors carefully explain, the reasons for this choice are mostly not technical. This is a design book and there is more to design than technical optimisation. Let the alert reader keep reading to find out the key to this conundrum. One hint: computer scientists largely agree that the novel, often truly astounding technical performance of today's computational tools is the main reason for many recent breakthroughs in AI. Yet there is more to today's dataism than a linear accretion of information and processing power; what some computer scientists call, somewhat dismissively, brute force computing is in fact a new set of problem-solving methods (hence a new kind of science) triggered by today's unprecedented data affluence and computing speed. In architectural history, however, the term brutalism has a quite different lineage and harks back to a different set of meanings and values. Considering where and when this is happening, and what is at stake for the present and future of the world in which we live and of the ideas in which we still believe, the rise of a new school of computational brutalism in design, conspicuously drawing from both traditions, is not coincidental.

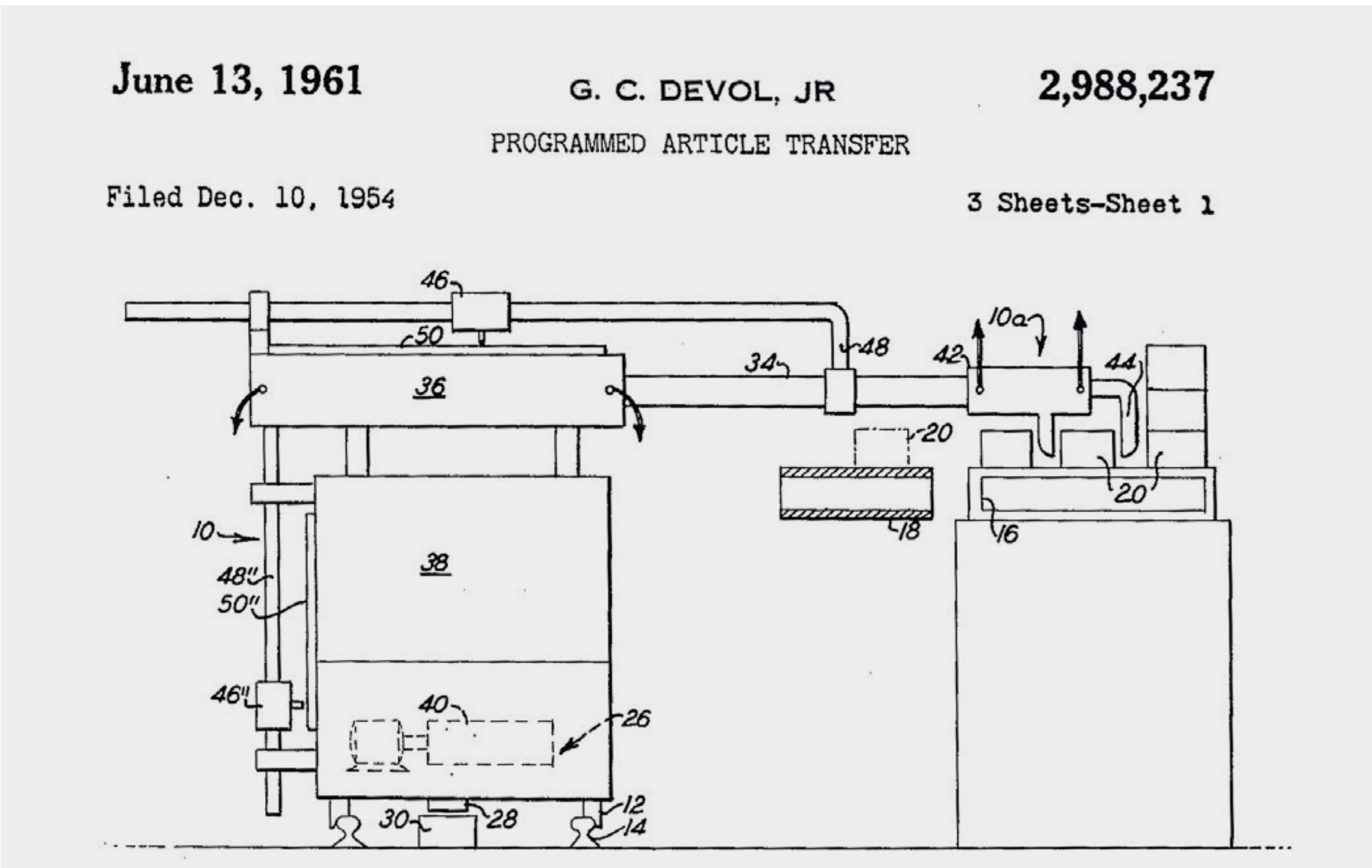
London, March 2019

Introduction
Architecture in the Age of Automation

Digital Architecture Does Not Exist

This book attempts to create a larger discussion around what we are calling robotic building, putting it in a context of automation. Robotic building is defined as the utilisation of robotic technology to realize architecture. Unlike previous books on robots, this is not a book that exists only in the context of digital fabrication or digital design. It considers robotic building as a form of automation and tries to identify the impact automation has had and will have on architecture and our built environment. This book is also not about the narrow definition of a robot as the orange industrial arm. Instead this book aims to kickstart a discussion about architecture in the age of automation, setting up questions for what architecture could be and what architectural production may look like once human labour is obsolete.

This recontextualisation around automation is important. Digital design is a method, using software developed originally in the film, aeronautical and naval industries in the late 20th century. The same applies to digital fabrication, which emerged in the same period from technological developments such as the CNC machine in the automobile industry and stereolithography in engineering. These two terms together, digital fabrication and digital design have resulted in something problematically described as digital architecture. As has been argued by many, digital architecture does not exist: [fn. 1] we have never been digital (until now). [fn. 2] Digital architecture is therefore not a paradigm – digital design and digital fabrication are technical methods that we as architects and designers use to create. Architecture and design are more than just methods, they are also positions that architects take towards what they see in the world. As positions, they are ways to structure the world, to



Unimate – the first industrial arm, George C. Devol Jr, 1954 speculate on it, to project into it, to propose possible futures for it. Positions are political. Methods are not.

As methods rather than paradigms, digital design, digital fabrication and digital architecture have been appropriated, historicised and politicised by actual paradigms as well as positions that are attempting to be paradigms – such as Patrik Schumacher's parametricism [fn. 3] and his alignment to a position in support of deregulation and the privatisation of public space. [fn. 4] This method is a neoliberal one, which is "logically consistent with the conformity of this architecture to the commodity form." [fn. 5] Or these also may include the austerity chic of Pier Vittorio Aureli [fn. 6] and DOGMA. [fn. 7] Or these could include the post-digital, i.e. what Adam Fure and Ellie Abrons have written is "both a continuation and interrogation of what we have known as 'the digital' to date", something "that doesn't simply represent the real – but is itself another real." [fn. 8] Or maybe the post-digital is what Mario Carpo has described as "a ruse de guerre engineered by a lobby of good old techno-bashers in disguise"? [fn. 9] Who knows. What we know is that we have never been digital, so how could we be post-digital? [fn. 10]

Architects, designers and researchers who do not want to be absorbed or framed under others' paradigms have been arguing for their work as craft and themselves as a new kind of neo-Ruskinian digitally-augmented craftsperson. [fn. 11] This kind of argument suggests that this work is somehow too lay or too common. A return to this kind of familiar design vernacular indirectly oppresses and hides the reality of how new systems of production have constructed societies of inequity worldwide. This position could be understood as reactionary, as it is not interested in repetition or accessibility, but operates through exception, for the few. It could be argued that this is a kind of head-in-the-sand act, one symbolic of the privilege of architectural discourse. Historically, it is not dissimilar to Art Nouveau or the Arts and Crafts movement, which reacted to the age of industrialisation by making one-of-a-kind works for the elite financiers and industrialists of the time as a reactionary cosy blanket to protect them from the impending doom of industry. The potentially revolutionary social qualities of the Arts and Crafts movement were grounded instead on values about beauty, tactility and the importance of place and therefore, material. Potentially the digital craft-based approach could be taken onboard strategically if it does not also take with it the same kind of apolitical Ruskinesque baggage – but we have yet to see this be attempted.

And yet others working within the context of today's universities, places reliant on externally funded grants, have to present their work as mainly technical. They are effectively forced to dodge the why question, while others can then pick up this knowledge and use it for their paradigm. At the same time, these methods have been discussed minimally in relation to the concept of the digital economy [fn. 12] – which is in fact one of the most important and pervasive aspects of the digital. [fn. 13] The digital economy is where companies such as Uber, Facebook, Tencent, Alibaba, Amazon, Google and Airbnb start to change the way we live, work, move and communicate. It is only in the last few years that architects have begun to take this more seriously, primarily due to the real estate and construction industries beginning to adopt blockchain and smart contract technologies. This shift holds the potential to revolutionise the way in which we understand ownership of land and other forms of property.

Automation is a Design Problem

The book proposes rephrasing the ongoing debate about digital design, digital fabrication, digital architecture and digital economy and to use the word automation instead. Automation today parallels the relationship between the industrialisation of production in the 19th and early 20th century and modernism. The Industrial Revolution and the modern period that followed was a time of debate, discussion and reforms regarding a right to housing, a healthy living environment and to a minimum income – i.e. issues that are very much prescient today.

Industrialisation transformed the culture and politics of architectural production, releasing reliance on the local – whether labour or material resources – and recalibrating production to existing on a large global scale. Of course, modernism then turned that same industrialisation into a social and aesthetic project that was meant to serve the lower and middle classes by providing them with mass housing. A sterile, white, colonialist, universal modernism has proven problematic, but the Fourth Industrial Revolution fn. 14 has yet to make as great a leap as the Industrial Revolution did with modernism. As Thomas Bock and Silke Langenberg noted over four years ago, robotics in architecture will require "a fundamental change in the early design stages as well as in the construction process that goes far beyond imitating existing building technologies." fn. 15 This change has yet to occur. The manner in which digital design and digital fabrication have translated into construction over the last decade or two has created a problem of infinite degrees of differentiation and variation for the sake of mass-customised forms. We refer to this later in Chapter 3: Assemble, but Skylar Tibbits described this best when he wrote:

> *"[…] architects have collectively pushed the boundaries of mass-customised complexities, producing thousands of unique components requiring thousands of connections that demand hours, days, months or even years of manual assembly. The energy input and man-hours necessary to build these structures, however, has generally been overlooked. They have been celebrated with impressive simulations. Beautifully nested cut-sheets, videos of CNC machines running 24/7 and stunning photographs hiding the assembly problem."* fn. 16

By using the term automation instead of digital + X, we can make the acknowledgement that the digital is now diffused into our everyday lives. There is no need to continuously use the term to indicate that this or that has involved the use of a computer. But it is obviously not diffused into the way we build. The point is not being digital but using it for something.

The term automation recognises that we are already past the moment where the change that Bock and Langenberg highlight could have occurred. Yet we are in the midst of a massive industry-wide assembly problem. So how do we invoke change?

As Evgeny Morozov has pointed out, large-scale automation needs to also be understood as a political issue, not only a technological one. fn. 17 Robotic building then is not just a technical problem to be solved. As we will see explored in later chapters, the technical problems that architecture as a discipline believes itself to be facing are problems that no longer exist in many other disciplines, from mechanical engineering to artificial intelligence. fn. 18

Nor is robotic building purely an artisanal craft. It is political. In this, it is cultural, it is economic and it is social. Automation does not distinguish between design and fabrication or even economy. Automation instead directs us to a point on the horizon: the obsolescence of labour.

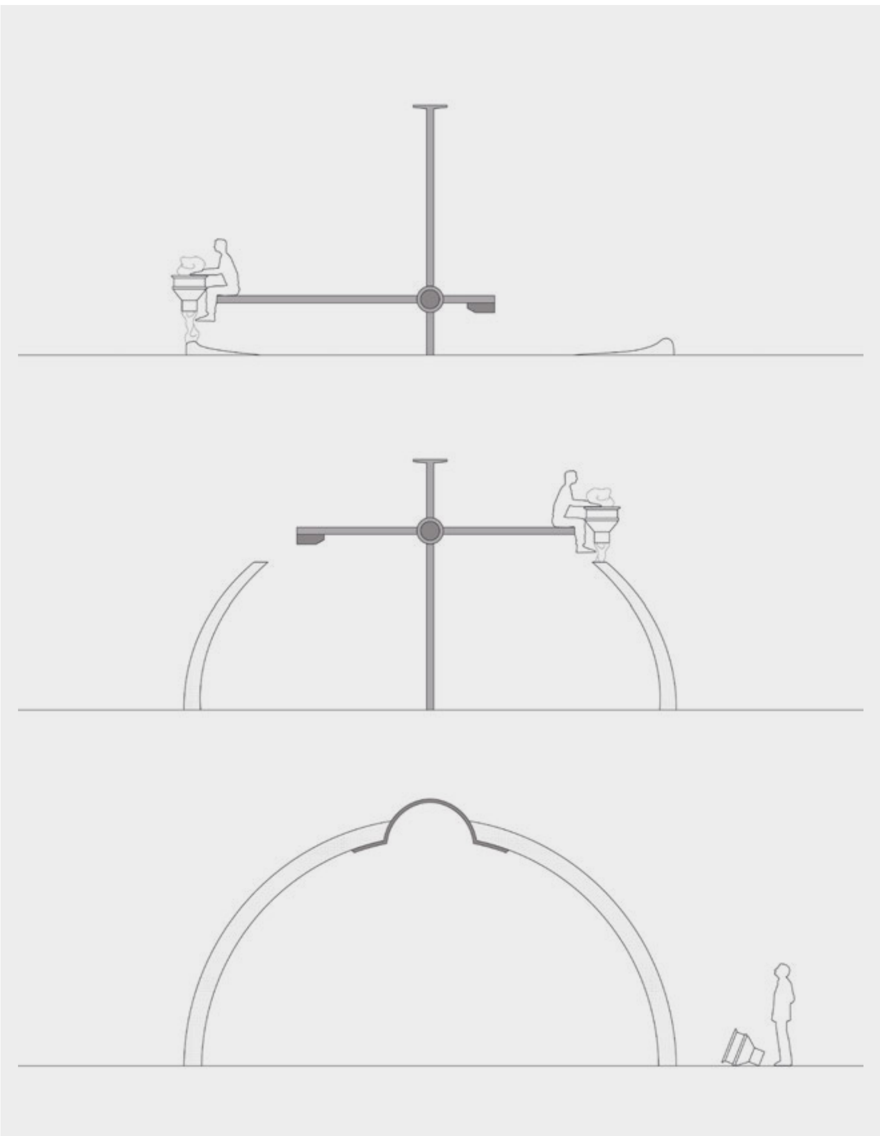
Automation and robotic building are connected to discourse on artificial intelligence, machine learning, Big Data, augmented reality, smart cities, labour, post-work society, capitalism – they have an all-encompassing impact on the way we structure and inhabit the world. It is connected to how these inform discourse around capitalism, post-capitalism and labour. Whereas digital architecture is innocent, automation is not. It immediately forces positions, questions about what a fully automated society would mean – do we all need universal basic income? Who owns the robots? Which jobs remain? Will we all live in WeWork-like housing? When we use the term automation, architects are suddenly able, or even forced, to think about labour, platforms, data, about jobs being lost in new rustbelts, about control and ownership. We need to be more rigorously considering the way in which the knowledge we develop about automation contributes to a better society as we face the challenges of the climate change Year Zero countdown, the housing crisis and rising inequities around the world. Automation is an inclusive platform where the politics of design meet social and economic concerns and can be discussed. fn. 19 The term digital design could never allow us to do that – but now we can. We can program robots while debating washing machines and design our own Airbnb while simultaneously thinking about interfaces in artificial intelligence – all through automation.

Bosch washing machine, 2019

Robots Should Not Do Nothing

This book aims to provide some clarity about the term robot in architecture. The term originally comes from the Czech word robota which means forced labour. It was first used in the second decade of the 20th century by the playwright Karel Čapek in his play R.U.R. (Rossum's Universal Robots) (1920). In R.U.R., robots were described as "artificial people" fn. 20 who met the "minimum number of requirements." They were not to feel emotions, be honest or hardworking or have a soul. Robots were basically to be as dumb and simple as possible. And in their simplicity, they were to be more mechanically perfect and intelligent than humans. fn. 21 This at the time, of course, was a technological impossibility, and so robots were understood as fantastical and fictional creatures, even admired for just being a robot rather than a human. Isaac Asimov's 1942 story "Runaround" in his book I, Robot outlined "The Three Laws of Robotics", protected the autonomy of a robot (Third Law) while also ensuring human safety (First Law) and human control (Second Law). fn. 22 The dangerous fantasy of robots was being hemmed in. The first industrial robot, Unimate (your universal mate or in a darker interpretation, your one friend), a handling machine in a General Motors factory in New Jersey in 1961, was used in diecasting processes to protect workers from hot metal and dangerous welding conditions. However, despite these very early developments, a form of fantastical fictional narrative persists today: the potential for a robot to be dumb, simple and still smarter than you. This robotic narrative has become cultural baggage that in architecture we just can not seem to shake off. fn. 23

Through the notion of automation, this book tries to steer clear of treating robots as gimmicks or fantastical creatures. We ask: what is a robot? What is the role of the robot beyond mere automation? More specifically, what is the role of the robot besides being an artificial person? Is it the physical machine or is it the series of protocols that drive the machine, e.g. the physical robot versus the virtual robot? In the broadest sense, a robot could be any machine that can carry out complex actions and does not require human control to operate. A drill is not a robot, as it needs to be controlled and handled by a human. A washing machine, on the other hand, can be considered a robot, as it runs automatically and does not require human control. So is a vending machine or a home thermostat. But let us be more specific: what is a robot in architecture? We can return to its original description by Čapek: simple, dumb, yet more intelligent and mechanically perfect than humans. A robot needs to be able to work well beyond human capacity and capability, doing things that no human could possibly do as efficiently and effectively. Yet they are often used to do supremely dumb tasks that are merely replacing human labour, but not doing as great a job as humans would: laying bricks fn. 24 or serving drinks. fn. 25



Drawing of Dow Chemical's Self-generating Styrofoam Dome by Clara Jaschke, 2019

Automate or Be Automated

Data from McKinsey and the UN shows that construction is one of the least digitised industries and also one where productivity has not risen since World War II. fn. 26 At the same time, we have a global housing crisis, where the amount of housing produced is steadily below the demand – in England alone there is a reported need for 240,000–340,000 new homes every year, with a huge backlog. fn. 27 The global housing crisis is not a crisis of production or even a crisis of technology – it is a crisis of capital. If the cost of constructing a building is only a fraction of the price it sells at, then the efficiency of production does not matter. This has been pointed out brilliantly by Reinier de Graaf, who mentions the absurdity of the discussion about a cardboard cladding for One Hyde Park, the most expensive residential property in the world. fn. 28 This seems to be a unique moment in time where the value of something is completely disconnected from the labour that went into it at an unprecedented scale. It also seems to suggest that even when fully automated from design to fabrication to assembly, the price of housing would still remain too high. This is where the importance of thinking in terms of automation – not digital design or digital fabrication – comes to the fore, as it provides the potential to rethink an existing market. It provides an opportunity to be disruptive.

Moreover, it is important to understand that if we as architects do not develop and question the different approaches to automation quickly – embedding it with cultural and social questions, then the big tech companies will do it. This is already happening. We have Google's SideWalk Labs developing Toronto's Eastern Waterfront, fn. 29 sparking debates about harvesting data and the colonisation of public spaces by large corporations. fn. 30 At the same time, construction start-up Katerra has sourced almost $1 billion in funding to mass-produce homes. fn. 31 Airbnb's Samara project will start building houses this year. fn. 32 Companies such as WeWork are actively buying up property in the centre of cities all over the world fn. 33 – in January 2018, WeWork became central London's biggest leaseholder of office space. fn. 34 These companies have a vested interest in automation – and will at some point be in the position to determine how our built future will look. If architecture doesn't quickly wrap its head around automation but instead keeps it in the sand, concerned with methods, craft, style or form, the discipline will have little say in the how or why this transition takes place.

The Fab Lab Will Not Save Us

The 1990s and early 2000s paradigm of mass customisation has inscribed itself into a neoliberal economic system fn. 35 where consumers are given the opportunity to customise and individualise products so that they become unique within the system. Although the product is fundamentally the same for everyone, it gives consumers the illusion of being acknowledged for their individuality. The idea of flexibility and adaptability is not in itself problematic, and indeed highly valuable for architecture and building construction, which is almost always in need of customisation to accommodate differences in briefs and contexts (environmental, social, material etc.).

The fab lab as a model for production has the potential to break this economic framework – putting the power into the hands of prosumers – or someone who produces the products that they then use. fn. 36 This enables an almost complete bypassing of the capitalist market, as prosumers only need to engage with that market in order to procure the materials necessary to make their products (if they cannot source them themselves). The fab lab, as a decentralised mini-factory for prosumers, would at face value seem to be a win-win for the consumer, who no longer has to be at the whim of the capitalist market. However, as Morozov has pointed out, the culture of the fab lab is linked to a political position – or better yet, a lack of politics – that comes from a Silicon Valley attitude where access to tools avoids the need for politics. Morozov describes the fab lab as a deeply neoliberal and libertarian world, fn. 37 portraying places such as WeWork (a sort of work-based fab lab) as "Hippy Taylorism". fn. 38 / 39

Similarly, digital fabrication projects such as Marcin Jakubowski's Open Source Ecology project assume a kind of complete tabula rasa erasing of society – where humans have to start building up a small community again from scratch because society has collapsed, using the Global Village Construction Set (2007–). fn. 40 Fab lab tools are always small-scale and do not need large collectives or societies to come together around an agenda or policy to achieve something. fn. 41 If we apply the definition of folk politics fn. 42 by Nick Srnicek and Alex Williams in their book Inventing the Future (2015) to the fab lab, then we can clearly see that the fab lab – as it has been deployed today – is a mechanism or strategy of mega corporations to diffuse power and force prosumers to be at the will of a broader desaturation of economic consumption. All under the guise of "but you can make your own X and say goodbye to the mega corporation!" In this current model, the fab lab will not save us.

At the same time, the qualities that fab labs have developed are indeed extremely useful because of their agile, light-touch and short production chain. We will discuss the implications of more in Chapter 2: Print. But before then, is it possible that this model could be taken over without the implicit political framework? Srnicek proposes that it is possible for progressive accelerationism to appropriate the technologies of capitalism where they are useful. fn. 43 Scalability and ownership are two key issues with fab labs as they are used today – they are effectively stranded in the area of maker-direct action movements. In this, we can look to the work of Jose Sanchez for some clues. Sanchez has argued that there are four principles that must be preserved in order for democratisation of production to happen on a larger scale. Those are parts, links, patterns and commons. fn. 44 A commons could be a wiki-like platform that can make architectural construction again accessible to the masses, with the use of creative commons licensing and open-source. Of course, WikiHouse (2014–) is one such model of this already deployed – but it has its limitations in terms of materials, which has a knock-on effect of limiting scale. A wider engagement with network technologies and a different understanding of production could possibly allow this scalability to occur, but only if there was greater engagement with the question of ownership of these kinds of platforms on a larger scale.

This is Robotic Building

This book is somewhere between an edited book and a monograph. Each chapter is framed through a different one-word theme, Craft, Print, Assemble, Many, Diffuse. We explore each theme in an introductory text before the project contributions, which helps us frame existing positions towards automation, digital design, digital fabrication and labour, historically and in contemporary architectural culture. The intent is for these themes to act as a lens through which to understand the meaning and value of the projects that we have included for the future of robotic building, as well as the current and future states of automation in architecture.

In addition, the project contributions that have been included are mostly built works. This is a strategic choice – we are not interested very much in the purely speculative. Projects which are more speculative in nature still tested their ideas at the scale of a built prototype of some kind. International in composition, the architects who have completed these projects are at the forefront of testing robotic building on a larger scale. They are often embedded in institutions such as ETH Zurich, Tongji University, University of Stuttgart, Sci-Arc and others who are pushing boundaries in the use of robotic technologies and have been for many years, as well as a younger generation of architects and designers who are emerging as important figures in work on robotic building.

Furthermore, the projects included are from the last seven years. This is the period in which we can trace the emergence of our critique regarding digital design and digital fabrication that forms the basis of this book – the period of Carpo's second digital turn from 2012 until 2018. fn. 45 It is also the period in which we have worked together as architects, researchers and educators at The Bartlett School of Architecture, although Design Computation Lab was founded only in early 2017 with the release of our first project, the Voxel Chair 1.0.

It is important to point out that we aim to make some sort of statement by putting the chapters in the order we have chosen. We are, after all, aiming to problematise, poke and punctuate the issues with robotic building and automation that we see as most important today. Our own agenda as a research lab is embedded within the ways we set up the chapters, the discussions and the project contributions. We hope that, even though there is an agenda in each theme, readers recognise that each of these themes can still exist simultaneously as they cross-pollinate each other and share some of the same conceptual and theoretical issues. The themes function similar to Alejandro Zaera-Polo's relational ecology of post-2008 practice, fn. 46 and we focus on the ways in which they can act as possible projections for methodological frameworks – not methods – for robotic building, rather than a singular historical narrative about robotics in architecture. However, it is precisely because of the position we take throughout the book on how automation is a design problem related to the politics of architectural production that each project is located where it is. We hope that these decisions and inclusions help recontexualise, illuminate, speculate, provoke and problematise what robotic building is in the age of automation.

fn. 1 Neil Leach, “There is No Such Thing as Digital Design”, in David Gerber, Mariana Ibanez (eds.), *Paradigms in Computing: Making, Machines, and Models for Design Agency in Architecture,* Los Angeles: eVolo Press, 2014, 148-158.

fn. 2 Gilles Retsin, “Discrete and Digital”, *TxA Conference Proceedings,* 2016.

fn. 3 Patrik Schumacher, “Paramectricism as Style – Parametricist Manifesto”, 2008, accessed: https://www.patrikschumacher.com/Texts/Parametricism%20as%20Style.htm.

fn. 4 Patrik Schumacher, Keynote: “Housing as architecture”, World Architecture Festival, December 2018.

fn. 5 Douglas Spencer, *The Architecture of Neoliberalism,* Bloomsbury, 2016, 73.

fn. 6 Pier Vittorio Aureli, *Less is Enough,* Strelka Press, 2013.

fn. 7 Alejandro Zaera-Polo, “Well Into the 21st Century The Architectures of Post-Capitalism?”, *El Croquis N.187,* El Croquis, 2016.

fn. 8 Adam Fure and Ellie Abrons, “Postdigital materiality”, *Lineament: Material, Representation, and the Physical Figure in Architectural Production,* ed. by Gail Peter Borden and Michael Meredith, Routledge, 2018, 185-186.

fn. 9 Mario Carpo, “The Post-Digital Will Be Even More Digital”, *Metropolis Magazine,* July 5, 2018, accessed: https://www.metropolismag.com/ideas/post-digital-will-be-more-digital/.

fn. 10 Gilles Retsin, “Discrete and Digital”, TxA Conference Proceedings, 2016.

fn. 11 Antoine Picon, “Robots and Architecture: Experiments, Fiction, Epistemology”, *Architectural Design,* Volume 84, Issue 3, Made by Robots: Challenging Architecture at a Larger Scale, May/June 2014, John Wiley & Sons, 58.

fn. 12 “The new digital workshop [starts to look] less and less like an incubator of new forms of participatory creativity, and more and more like a playground of corporate interests, bureaucratic opaqueness and technocratic megalomania,” found in Mario Carpo, “Authoring in the Digital Age”, berfrois, 25 February 2011, accessed: https://www.berfrois.com/2011/02/mario-carpo-post-authorial-creation/.

fn. 13 Although, as we will see, it has been discussed in the context of the fab lab.

fn. 14 Klaus Schwab, *The Fourth Industrial Revolution,* The Fourth Industrial Revolution, 2016.

fn. 15 Thomas Bock and Silke Langenber, “Changing Building Sites: Industrialisation and Automation of the Building Process”, *Architectural Design,* Volume 84, Issue 3, Made by Robots: Challenging Architecture at a Larger Scale, May/June 2014, 90.

fn. 16 Skylar Tibbits, “From Automated to Autonomous Assembly”, *Architectural Design,* Volume 87, Issue 4, Autonomous Assembly: Designing for a New Era of Collective Construction, July/August 2017, 8.

fn. 17 Evgeny Morozov, *To Save Everything, Click Here: Technology, Solutionism and the Urge to Fix Problems that Don’t Exist,* Allen Lane, 2013.

fn. 18 Philippe Morel, “Computation or Revolution”, *Architectural Design,* Volume 84, Issue 3, Made by Robots: Challenging Architecture at a Larger Scale, May/June 2014, 85.

fn. 19 Designing the Digital Economy, a report by the Design Commission, 14 May 2014, accessed: https://www.designcouncil.org.uk/sites/default/files/asset/document/Design%20Commission%20report%20-%20Designing%20the%20Digital%20Revolution.pdf.

fn. 20 Karl Čapek, *R.U.R. (Rossum’s Universal Robots),* transl. by Paul Selver and Nigel Playfair, 1920, 4.

fn. 21 Ibid, 9.

fn. 22 Isaac Asimov, “Runaround”, *I, Robot,* Street and Smith Publications, Inc., 1942.

fn. 23 See: *Towards a Robotic Architecture: even when they do nothing, robots are evocative,* eds. Mahesh Daas and Andrew John Wit, ORO Editions, 2018.

fn. 24 SAM100, Construction Robotics, 2016.

fn. 25 A few years ago, at the Christmas party of our home institution, this was how one (two? The night is hazy) of our workshop’s ABBs was used. It took ages to get a drink, but everyone wanted one poured by our robotic bartender – the line was well out of the door.

fn. 26 “Reinventing Construction: A Route to Higher Productivity”, McKinsey Global Institute, McKinsey & Company, February 2017.

fn. 27 Wendy Wilson, Cassie Barton, “Tackling the under-supply of housing in England”, Briefing Paper, House of Commons, December 2018.

fn. 28 Reinier de Graaf, “Architecture is now a tool of capital, complicit in a purpose antithetical to its social mission”, *The Architectural Review,* April 24, 2015, accessed: https://www.architectural-review.com/essays/viewpoints/architecture-is-now-a-tool-of-capital-complicit-in-a-purpose-antithetical-to-its-social-mission/8681564.article.

fn. 29 https://www.sidewalklabs.com/

fn. 30 See T.F. Tierney’s work on this subject titled “Testing the Urban Stack: Sidewalk Lab and Toronto’s Eastern Waterfront” was presented at the 2018 ACSA/COAM International Conference New Instrumentalities in 2018.

fn. 31 Michael J. de la Merced, “Katerra, a Construction Start-Up, Raises $865 Million”, *The NY Times,* 24 January 2018, accessed: https://www.nytimes.com/2018/01/24/business/dealbook/katerra-softbank-vision-fund.html.

fn. 32 Mark Wilson, “Exclusive: Airbnb will start designing houses in 2019”, *Fast Company,* 29 November 2018, accessed: https://www.fastcompany.com/90271599/exclusive-airbnb-will-start-designing-houses-in-2019.

fn. 33 “WeWork’s $47 Billion Dream: The Lavishly Funded Startup That Could Disrupt Commercial Real Estate”, Research Report, CBInsights, accessed: https://www.cbinsights.com/research/report/wework-strategy-teardown/

fn. 34 Aime Williams,“WeWork becomes central London’s biggest office occupier”, *Financial Times,* 23 January 2018, accessed: https://www.ft.com/content/40a87044-ff97-11e7-9650-9c0ad2d7c5b5.

fn. 35 Douglas Spender describes this through the case study of Zaha Hadid Architects’ BMW Leipzig project, a project which for him exemplifies neoliberal managerial strategies. The language he uses is important in relation to this inscription of the early digital. The same could be said for companies such as WeWork today. He writes: “ … the company no longer even feigns concern with the welfare of its individual employees, but only – if and when these resources may be called upon – with their efficient functioning of ‘molecular’ components, as inputs and relays within an always adaptable system. It offers no commitment, and concedes no responsibility, to the worker. It deals only in opportunities – to be offered, held or withdraw as it determines economically efficient – to join its putative community on an always provisional basis.” Doulas Spencer, The Architecture of Neoliberalism: *How Contemporary Architecture Became an Instrument of Control and Compliance,* Bloomsbury, 2016, 88.

fn. 36 The prosumer was first described by Alvin Toffler in 1980 in his book *The Third Wave: The Classic Study of Tomorrow* (Bantam).

fn. 37 Evgeny Morozov, “Making It”, *The New Yorker,* 13 January 2014 issue, accessed: https://www.newyorker.com/magazine/2014/01/13/making-it-2.

fn. 38 Evgeny Morozov, "The digital hippies want to integrate life and work – but not in a good way", *The Guardian UK Edition,* 3 December 2017, accessed: https://www.theguardian.com/commentisfree/2017/dec/03/digital-hippies-integrate-life-and-work-wework-data-firms.

fn. 39 In architectural education, there are parallels to WeWork and fab labs in the notion of the visiting workshop, where precariously employed young designers are paid a pittance to work 24-7 to indoctrinate the willing. Yet, these workshops are often the spaces that allow design research to develop enough to gain employment in larger corporations or university settings.

fn. 40 https://www.opensourceecology.org/gvcs/

fn. 41 A possible alternative is provided here by Mariana Mazzucato who talks about mission-orientated policy-making. See her report for the RSA “Mission-Orientated Innovation Policy: Challenges and Opportunities”, September 2017, accessed: https://www.thersa.org/globalassets/pdfs/reports/mission-oriented-policy-innovation-report.pdf.

fn. 42 Nick Srnicek and Alex Williams, *Inventing the Future: Postcapitalism and a World Without Work,* Verso, 2015, 9-13.

fn. 43 Nick Srnicek, *Platform Capitalism,* Polity Press, 2016, 126-129.

fn. 44 Jose Sanchez, “Combinatorial Commons: Social Remixing in a Sharing Economy”, *Architectural Design,* Volume 87, Issue 4, Autonomous Assembly: Designing for a New Era of Collective Construction, 19.

fn. 45 Mario Carpo, *The Second Digital Turn: Design Beyond Intelligence,* MIT Press, 2017.

fn. 46 Alejandro Zaera-Polo, “Well Into the 21st Century The Architectures of Post-Capitalism?”, *El Croquis N.187,* El Croquis, 2016, 255.

Chapter 1
Craft

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Craft

As described in the introduction, the origins of robotic thinking in architecture could be told through a multitude of narratives that range in nature from dystopian science fiction to the military and the sciences. If we take a broad look at the status quo of robotic thinking today, we can roughly differentiate these narratives into several present areas of research and development utilising robotic technologies. As the title of this chapter suggests, the automation of craft, or the use of robots to do artisanal actions (those of the sculptor or skilled labourer), remains one of the most important pursuits in robotic thinking. This area of work crosses important disciplinary boundaries between current discourses on the role that creative and cultural pursuits play in our contemporary society and speculative economic models for labour and automation that can and will inform and influence the ways we produce architecture. The three projects included in this chapter, Chi-She (2016) by Chinese architectural practice Archi-Union Architects led by Philip Yuan, Cyclopean Cannibalism (2017) by American architectural practice Matter Design led by Wes McGee and Brandon Clifford and the Elytra Filament Pavilion (2016) led by Achim Menges (Institute for Computational Design and Construction (ICD), University of Stuttgart), Jan Knippers (Institute of Building Structures and Structural Design (ITKE), University of Stuttgart) and Thomas Auer (Transsolar Climate Engineering, Stuttgart) are pioneering the way in which they use the robotic arm to efficiently and precisely replicate and reduce human labour, while achieving a level of complexity and resolution in building material and ability to respond to the surrounding environment that is not easily (nor cost-effectively) met using manual means alone.

The shared history of these projects is well-illustrated in early post-Industrial Revolution era speculations on the role and potential of automated machines in the design, fabrication and assembly of buildings. The French artist Villemard contributed drawings to a 1910 postcard series *En L'An 2000,* one of which shows an architect pressing buttons on an interface while sitting with a plan drawing on his lap in a small room just larger than a modern telephone booth. Several wires extend to various machines on a building site performing the typical tasks for constructing a building. The machines are coordinated to perform these tasks in a certain order to construct the building design, the plans for which are laid out in front of the architect.

The system proposed in this image is a single input system where a complex set of data is reduced by the architect to a coordinated series of actions to be executed by the robot (cut, pick up, carry, put down). The machines are highly differentiated; their specific automated, binary actions are in effect analogies for the human labour and skills required of a stone mason or labourer on site. However, the tasks typically embodied in the singular entity of the skilled stone mason are broken down into specific automated yet simple actions. The information that makes up these actions can be further reduced to the minimum required for the actions to be completed, i.e. it can be abstracted to the digits 0 and 1. The plan is thus reduced by the architect to code, which they then input into this highly discretised system.

A result of the Industrial Revolution, the advent and emergence of the scientific management of Taylorism and its later adaptation into Fordism hold a significant legacy in contemporary architectural design and other disciplines involved in the production of the build environment. Where Taylorism attempted to look holistically at social, political and economic relationships between systems of labour and production (i.e. the relationship between the architect and the machine), Fordism later drove much of the development of new tools towards efficiency and therefore cost-effectiveness (i.e. the replacement of specific acts of human labour with machines that take over those specific acts). Today, we see the effects of this play out in architectural offices and building sites all over the world. However as Fabio Gramazio and Matthias Kohler have written, "[…] the true significance of robots in architecture is not […] about being technologically up-to-date nor about obeying economic pressure to exploit such technologies […], the aim is an unbiased and therefore liberated use of technology in order to explore its true conceptual potential and architectural relevance." fn. 1 Therefore the automation of craft utilising robotic technologies should not be treated as only a means to an end.

So while in the Fordist framework of production the abstraction or reduction of human labour into specialised, simple tasks enables more efficient and cost-effective mass production of objects, it also embodies a total separation of mind and body. The task-specific robotic machine cannot perform any actions other than those it is designed to to execute – as in Villemard's drawing. It can only produce a building assembled out of cut blocks of material, stacked in courses of even, homogenous and regular distribution. What this kind of system therefore does not allow is for objects or buildings to be in any way different from one another without radically changing the design of the robotic machine itself, the data inputs the machine receives or the framework for production in which it is situated. This is obviously a highly inefficient way to produce architecture with technology, as it does not allow for any flexibility whatsoever – neither in the geometrical inputs, material distribution or type of material, design outcomes nor in the technology itself. And, importantly, architectural agency entirely lies in the hands of the master architect, a paradigm which today is being questioned and challenged. So how does one embed the possibility and potential of flexible outcomes – or variation, differentiation or heterogeneity – into the framework of robotic building and its processes and technologies? How can we think about the role of the architect in a way which allows for craft-like agency to be embedded in material or within robotic technologies?

Fordist assembly line, Henry Ford, 1913

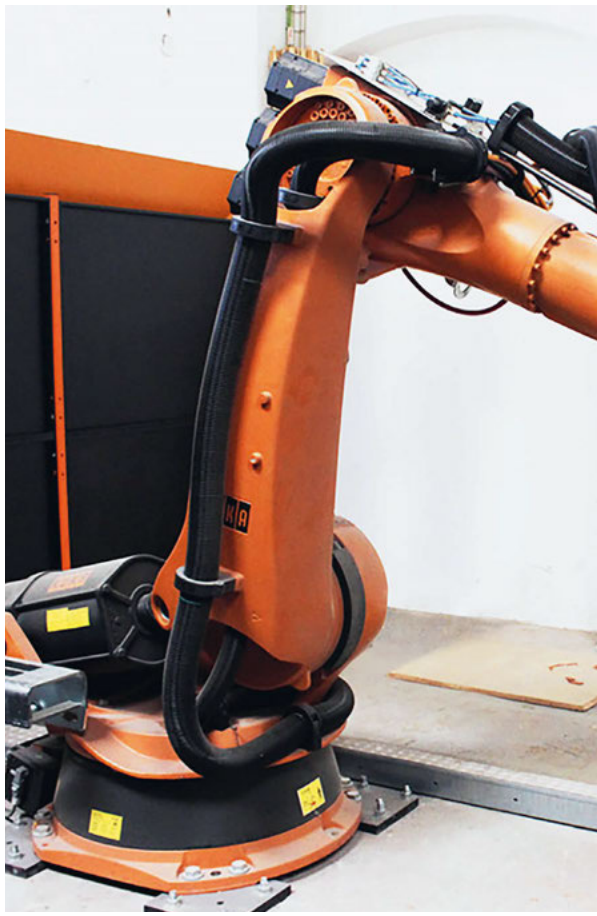
From Mass Standardistion to Mass Customisation

The last thirty years of work in architecture interested specifically in embedding procedural or operational thinking into design and fabrication processes provide a number of possible answers. Written about at length by architects, historians, theorists and critics interested in the digitisation of architectural design, fn. 2 the beginning of this period was epitomised by the adoption of post-Fordist frameworks for production in architecture. Emerging in the latter half of the 20th century as the primary model for economic production, post-Fordism is characterised by a shift towards the fragmentation of labour (and thus specialisms), processes (and thus tools/technologies) and, importantly, mass customisation (and thus the individual consumer) over the mass-standardisation of the continuous Fordist assembly line – though this list of characteristics is not exhaustive. Post-Fordism's translation into architecture is clearly characterised by this shift from mass standardisation towards mass customisation in the latter half of the 20th century.

The notion of infinite numbers of variant but self-similar architectural objects was a core concern of architects during the 1990s and early 2000s. The development of processes for mass customisation and heterogeneous objects in this period was an extension of the "pre-conscious digital" fn. 3 of Peter Eisenman and before him, Colin Rowe, found in Eisenman's architecture of autonomy of the 1970s and 80s and in Rowe's formalist contextualism as exemplified by Collage City (1978). "Digital before the digital" fn. 4 projects such as Biozentrum (1987) by Eisenman Architects adopted early accessible personal computing technologies in order to explore concepts drawn from biology such as adaptation and morphogenesis as well as from the philosophy of Gilles Deleuze, particularly his work *The Fold: Leibniz and the Baroque* (English translation 1993). Adoption of animation software from the film and aeronautical industries, such as Alias and Wavefront (later merged into Maya) or SoftImage (the successor to Softimage|3D), and of hardware such as computer numerical control (CNC) machines, by architects such as Greg Lynn and Bernard Cache further allowed morphogenetic and topological thinking to be embedded in architectural disciplinary culture.

As Lynn theorised in his book *Animate Form* (1999), an architecture of difference – informed by the differential calculus of Leibniz via Deleuze – was against the static and passive architecture of tradition. Lynn was diametrically opposed to the derivation of architecture from fixed points in space – geometrical, material, spatial – that existed in an ideal Cartesian set of coordinates. fn. 5 The active and dynamic architecture that Lynn and others, such as Foreign Office Architects and NOX, proposed during this time instead conceived of form as acted upon by forces, which would always remain in relationship to one another through the way that they were embodied in a particular form.

With the help of software programmes, a series of curves, represented by a mathematical mode known as NURBS curves, were connected to form the overall shape of an architectural object. The shape of the curve can be adjusted by changing the position of a set of points known as control points. The form of the architectural object had both a generic primitive in a set of interconnected points along the lofted curves and the capacity for infinite variables of this topology to be crafted. The control points on the NURBS curves were adjusted in relationship to

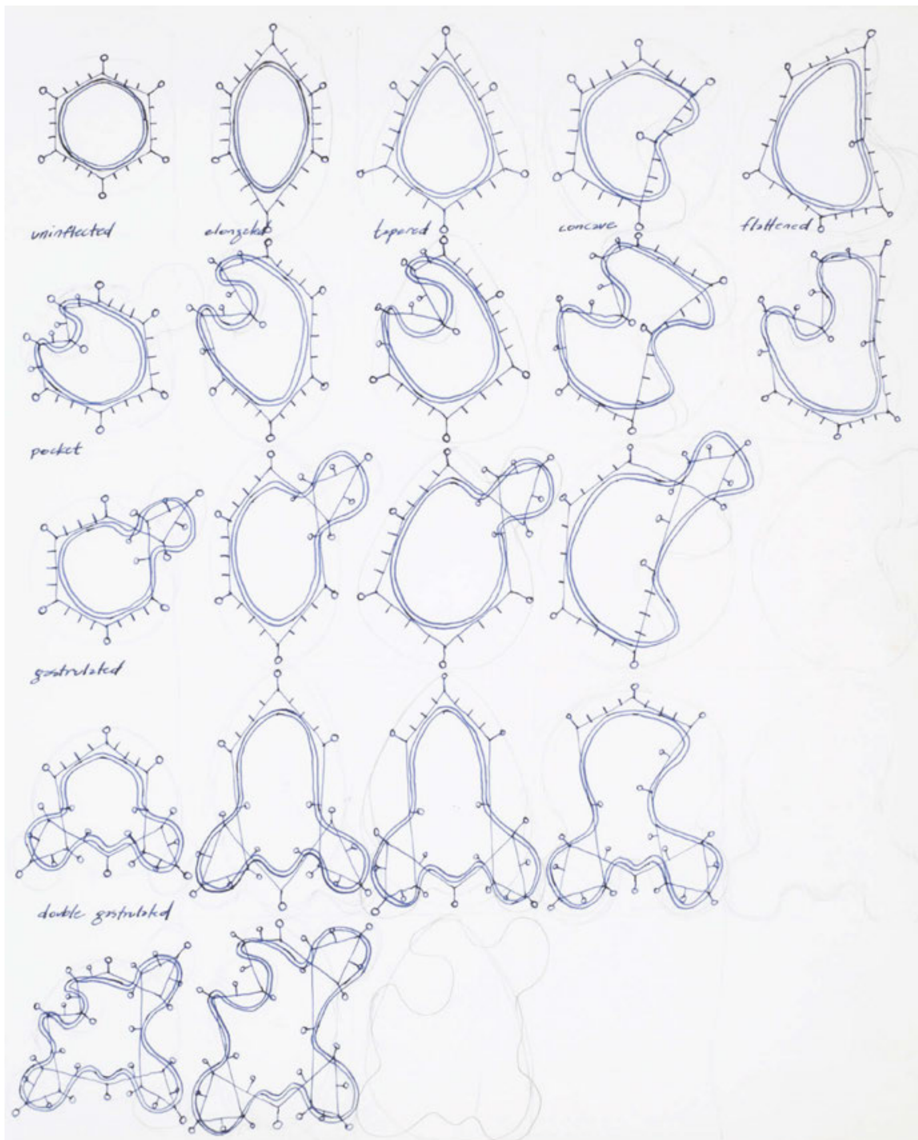


FabClay, Nasim Fashami, Sasa Jokic, Starski, Marta Male-Alemany, IAAC, 2012 external or “contextual”, forces, and as a result they would also shift in relationship to one another producing many – infinite – instances of the same object. This form was typically later translated into a surface that would become a building envelope and structure.

As the variations of objects were constructed by a series of interconnected lofted lines, this kind of process lent itself towards prevailing fabrication strategies of the time. Typically the objects were sliced into sectional cuts or frames to be cut, for example, using a 2- or 3-axis CNC milling machine. These frames each had the same number of control points on them, but if these control points were moved along a single axis, there emerged a set number of differentiated surfaces per section cut. [fn. 6] No two surfaces between frames were the same. In the case of the Embryological Houses (1997–2001) by Lynn, further customisations of the overall form, envelope and foundations could be made via a web app by consumers. This allowed for a degree of input by users/consumers in the crafting of the house, although within predetermined limitations set by the architect – the options were finite. [fn. 7] This set of infinite but constrained variations is known as the design space.

The Agency of the Digital

The impact, potentials and limitations of this kind of system for design and fabrication can be reflected upon critically today, particularly when considering the efficiency of the fabrication and assembly strategy that was used during the first Digital Turn. [fn. 8]



Embryological House, Greg Lynn, Greg Lynn FORM, 1998

CNC machines, best used to fabricate with precision, began to be used to produce non-standard, variable parts. However, fabricating variation resulted in a large amount of material wasted due to non-standardisation, and a large amount of labour required in order to assemble these frames and panels. While mass customisation was achieved by embedding procedural thinking in the design process, the framework of production using automated technologies was in effect very slow, highly discrete and laborious, with little feedback from the production methods back into the design process, and so not much different from the production framework in Villemard's illustration. Practices such as Objectile (Bernard Cache, Patrick Beauce and Jean-Louis Jammot) approached the issue of mass customisation in a different way, by addressing the very nature of the software and hardware they used. Rather than using software intended for mass-customisation, Cache opted for programs used predominantly by industrial engineers for mass production – commonly referred to as "File to Factory" – which were then modified as required. Relying on software meant to be used with CNC machines made a "fully associative design and manufacture" fn. 9 process possible, in which the design and the means of manufacturing shared the same syntax, i.e. they were both made of digital numerical data. Instead of the opportunities for infinite topological variations of a single generic object, in Cache's associative architecture there were geometrical and numerical limits that were set in relationship to the manufacturing procedures and programs needed to produce an object. All the pieces and parts necessary to construct an architectural object – such as the Semper Pavilion (1999) and the Philibert De L'Orme Pavilion (2001) – were generated in relationship to one another, and were programmed for manufacturing in relationship to one another. As Cache explains, the design procedures used to generate the object relied "on a limited number of geometrical and numerical parents that can be easily modified and can then regenerate the whole design." fn. 10 Additionally, although this geometry can be crafted or "regenerated" within a procedural design to manufacturing framework, it is extremely labour-intensive in the design process. Cache himself wrote that when dealing with an entire building there could not be "a piece of software written for each type of design problem." fn. 11

As a framework linking both the digital or virtual model and design process with the constraints and possibilities of a manufacturing technology, the work of Objectile can be seen as a precursor for contemporary work utilising robotics in order to automate the

Robotic carving, Giulio Brugnaro, The Bartlett School of Architecture, UCL, 2018 crafting of architectural objects or even the construction of buildings. Today the industrial robot arm has capabilities far beyond the CNC machine and can have up to 6 axes and a reach radius of up to 1.5 metres. The industrial robot arm itself is completely generic and totally anonymous on its own. The generic and anonymous nature of the robotic arm thereby "reverses" the "image-machine organisation" that Bernard Cache attributed to the potential of the CNC machine thirty years ago. fn. 12 The industrial robot becomes specific only through the customisation of its end extruder and by how many axes it has (2, 4, 6, etc.) – essentially by giving it agency similar to the hand of the craftsman. It is through the exploitation of its versatility and customisability – as it can be used in a rigid or in a more flexible framework of design and production – that the industrial robot becomes at once closer to and in a sense more capable than the human body. If we then rethink the industrial robot arm as part of a holistic and procedural design and fabrication process for crafting an object – rather than as an isolated task-orientated machine fabricating only a part or an aspect of that process – we transform the way we think about the crafting of material and therefore the crafting of architecture.

The automation of the craftsman is thus one of many possible narratives or paradigms that originate in discourse around the power and potential of robots to deal with and transform our relationship to data and labour. The industrial robot arm in this model of thinking is used to empower, enable and take on characteristics and qualities of the craftsman or artisan. The data is extracted from the shape of a virtual object and the robotic arm performs actions related to how that shape needs to be crafted. The robotic arm and its end effector as the arm and hand of the potter or the chisel of the stone sculptor are images which have entered our contemporary condition. As an extension of the craftsman, the industrial robot narrows the mind-body dichotomy as it is given an ability to become intelligent and part of a feedback loop between material behaviour, manufacturing programs, design software, the user or context and the architect.

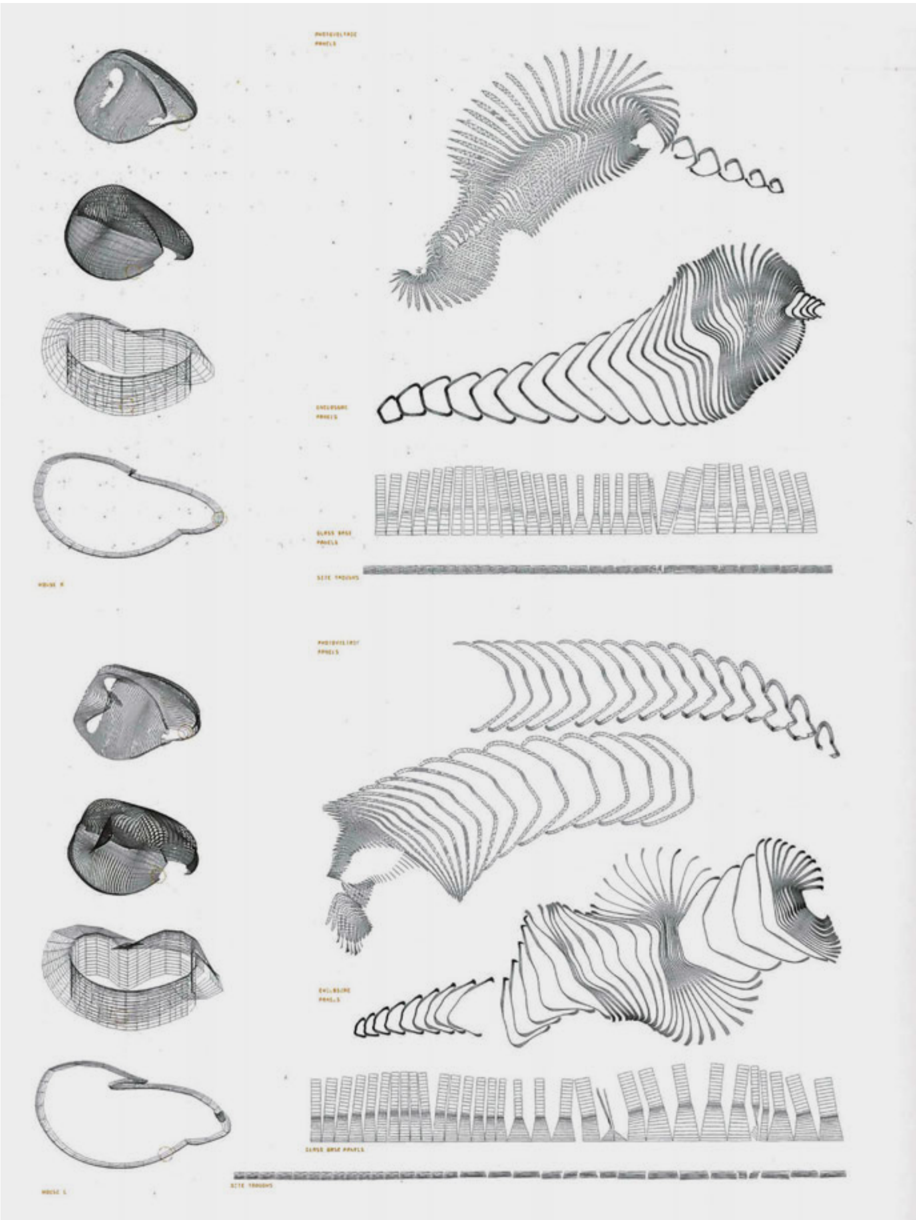
Prototypes for a System of Production

Capturing what has by and large been the state of the art in this area, the projects in this chapter highlight three contributions within this paradigm that have been completed in the last several years. The contributions, by Archi-Union Architects, by Matter Design and by the Institute for Computational Design and Construction at the University of Stuttgart (ICD Stuttgart), each utilise a single articulated industrial robot to craft material into customised, variable but recognisable architectural elements: wall (Cyclopean Cannibalism by Matter Design and Chi-Se by Archi-Union Architects) or column and slab (Elytra Filament Pavilion by ICD Stuttgart). The projects serve as progressive and forward-thinking prototypes, not just for the architectural element they embody, but also as prototypes of an entire system for the automation of craft in architectural production.

There are ways that the projects can be understood in relationship to one another. The first is the degree to which information about the behaviour and organisation of material by the robotic arm is fed back through the system or framework of production – something that we see as beginning to be possible in the work of Cache above. For example, in Chi-She by Archi-Union Architects, the design of the robotically-assembled brick wall is predetermined. The bricks, while salvaged from the building previously on the same site, are all the same, and do not have much differentiation in their composition or geometry. Because of this, the construction of the wall is relatively straightforward – as long as the robot's positioning is maintained manually by an on-site operator, it should distribute the building materials as planned and with a degree of precision and complexity otherwise impossible with manual bricklaying.

Additionally, the way in which human labour and knowledge is involved in the design and assembly of the objects differs between projects. This can relate to issues of authorship and therefore to how much a design is determined. This could also refer to the role of a material's behaviour and its inherent qualities and characteristics being embedded in the design and building process (if we anthropomorphise material, then we could refer to this as the material's knowledge). Specific to two of the projects is the degree to which any customisation or adaptation of the project occurs due to constraints that appear over the course of its construction. With one of these two projects, Cyclopean Cannibalism by Matter Design, dry stone construction techniques that have been used for centuries around the world are inserted into a contemporary framework of robotic building. After scanning, the rough stone is analysed and algorithmically placed into the best possible position in a wall structure. It is then minimally cut by robotic milling to fit and finally placed into the wall. The process that Matter Design uses drastically increases the precision in the crafting of material, and allows for real-time feedback of production data, in particular material behaviour and geometry, into the fabrication and assembly of the wall.

Furthermore, the projects included in this chapter are ones which address the wider organisation of the framework of production for the automation of craft, shifting the relationship of materials, humans and robots as discrete and separate entities to a relationship which is continuous and streamlined. The automation of craft makes this possible. The Elytra Filament Pavilion by ICD Stuttgart and Cyclopean Cannibalism by Matter Design both exemplify this shift, albeit on slightly different scales. The Elytra Filament Pavilion proposes an automated building system



Embryological House, Greg Lynn, Greg Lynn FORM, 1998 that crafts material and the overall geometry of the pavilion itself according to changes in environmental, structural or social conditions, using real-time sensor feedback to drive the adaptations of the pavilion over time. The synthesis of this information and adaptation of it in the pavilion proposes a fully digital process from design through to inhabitation that is enabled by robotic and other automated technologies. Together, these three projects enable us to speculate, challenge and propose a new state of the art for systems for the automation of craft in robotic building today.

fn. 1 Fabio Gramazio, Matthias Kohler et al. *The Robotic Touch: How Robots Change Architecture,* Zurich: Park Books, 2014, 246.

fn. 2 Notably the architecture historian Mario Carpo as well as several contributors to this book. Carpo extensively writes about and historicises the digital in his work, particularly *The Digital Turn in Architecture 1992 – 2012* (2012), *The Alphabet and the Algorithm* (2011) and *The Second Digital Turn: Design Beyond Intelligence* (2017).

fn. 3 Eisenman refers to the Biozentrum project of the late 1980s as embodying a “pre-conscious origin for the digital” in “Peter Eisenman in conversation with Greg Lynn”, CCA Channel, https://www.youtube.com/watch?v=DUrA1Lod--g accessed 20 September 2017.

fn. 4 Ibid.

fn. 5 Greg Lynn, *Animate Form,* Princeton Architectural Press, 1999.

fn. 6 Greg Lynn, “Embryological Houses ©” in *The Digital Turn in Architecture 1992–2012* (ed. Mario Carpo), John Wiley & Sons Ltd (2013), 126-130.

fn. 7 http://www.glform.com/embryonic/embryonic.htm

fn. 8 Mario Carpo, *The Digital Turn in Architecture 1992–2012* (ed. Mario Carpo), John Wiley & Sons Ltd (2013).

fn. 9 Bernard Cache, “Philibert De L’Orme Pavilion: Towards an Associative Architecture”, The Digital Turn in Architecture 1992–2012 (ed. Mario Carpo), John Wiley & Sons Ltd (2013), 153.

fn. 10 Ibid.

fn. 11 Ibid, 157.

fn. 12 Bernard Cache, *Earth Moves: The Furnishing of Territories* (English transl. 199X, originally published in 1988 in French), 95.

Chi-She Gallery, 2016
Archi-Union Architects led by Philip Yuan

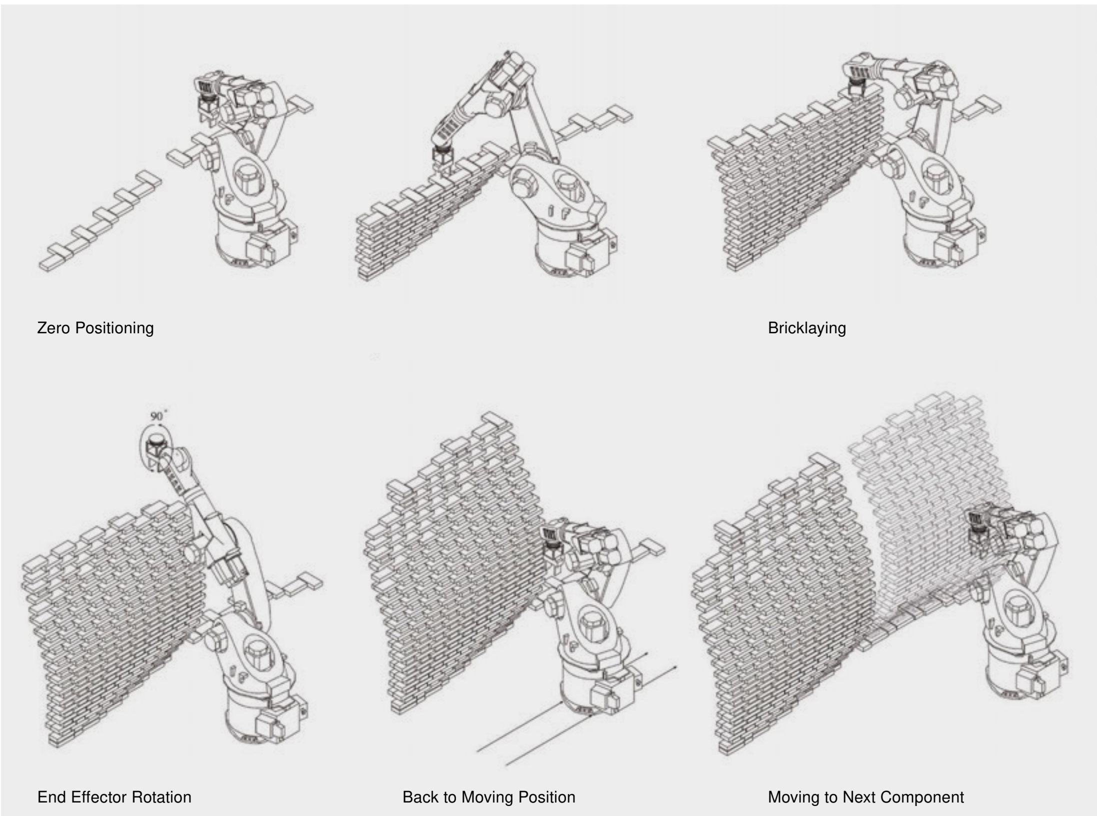
Located in Shanghai's West Bund Art Exhibition Area, the Chi-She Gallery by Archi-Union Architects seeks to evoke an enigmatic spatial appeal through the desire to both harmonise and integrate the building with its surroundings, while at the same time offering a formal expression of the artistic mission of the works contained inside. The existing exterior walls were retained, shored up and structurally reinforced as necessary to maximise the amount of interior space. In order not to affect the perception of the space of the area, part of the gallery's roof was raised to give those inside an unobstructed view of the sky. The roof structure was replaced by a more efficient, lightweight tensioned timber structure, a section of which was lifted to bring in light and connect those inside to the changing climate outside. Grey-green bricks were chosen to blend in with the existing structure and applied to the exterior surface to offer an interface with the public courtyard and the gallery entrance. The entrance wall has been warped slightly, as a form of architectural expression conveying current cultural trends. It is based on local tradition and expresses the vitality of the Chi-She community.

Such a complex form of masonry construction would not have been possible using traditional methods. Robotic masonry fabrication technologies were employed on site in order to achieve the desired outcome. The external walls were built using bricks salvaged from an older building and constructed with the help of an advanced robotic arm, which picked-and-placed the salvaged bricks into their designated position in order to generate the wall's curved surface.

The precise positioning of the masonry using robotic fabrication technologies transforms the traditional materials of bricks and mortar, allowing them to be seen in a new light. The integration of these salvaged bricks into a new stretch of curving wall narrates a story of people and bricks, machines and construction, design and culture, and is etched into the shadows of the external wall while the sun sets.

Integrated folding of elevation and entrance canopy
© Shengliang Su, Chi-She, Arch-Union Architects, 2016

Night view of Chi-She front elevation © Shengliang Su, Chi-She, Arch-Union Architects, 2016



Robotic fabrication diagram, Chi-She, Arch-Union Architects, 2016

Cyclopean Cannibalism, 2017
Matter Design led by Brandon Clifford and Wes McGee, with Quarra Stone

In Cyclopean Cannibalism by Matter Design and Quarra Stone, current knowledge fn. 1 of how the Inca and other ancient cultures constructed megalithic stoneworks provides insight for the project: these stoneworks were not the result of an architect predetermining and composing a design, then requesting stones to be quarried and carved to align with this conception, but rather selected from loose piles and minimally carved to bring a close fit into a precise fit. This architecture emerged through an intelligent sequential logic informed by the constraints of material and technological resources. These cultures intelligently cannibalised their own architectures, re-using material from earlier constructions to save on waste and transportation. In an era where we send debris from demolished buildings to landfill, Cyclopean Cannibalism demonstrates that we can learn a great deal from their knowledge.

Most pre-industrial civilisations carved their great works of architecture in stone, and often those works were built upon, adjacent to or a reconstitution of a prior civilisation's architectures. This method reduces waste and transportation, in favour of a craftsman's ability to template and customise stone. Though not possible under the industrial paradigm, the promise of the digital era fn. 2 primes us to reconsider the potential of this "primitive" way of thinking. With so much of the discussion surrounding digital design focused on topics such as serial variability, generative design and agency, one must consider that we have more in common with the Inca than we do with modern industrialism.

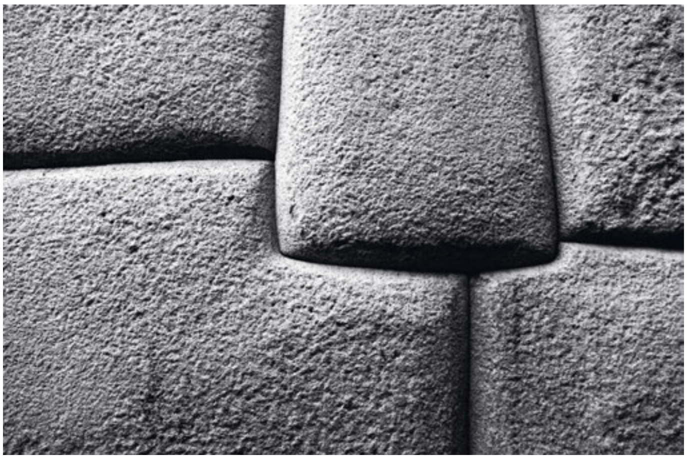
Recent advances in robotics coupled with real-time sensing allow us to move toward implementing adaptive processes within robotic building. In Cyclopean Cannibalism, the incorporation of sensor feedback into the production process can also occur at multiple levels, for example, making online corrections to the geometry of future components to adapt to deviations between a master digital model and a constantly updated as-built condition. The translation from design to production becomes a bidirectional exchange, whereby the overall design can adjust to results or in-progress changes to the system. This adaptive process must consider a range of inputs, including structure, fabrication constraints and formal considerations. It merges the intelligence of automation and computation with ancient algorithms to resolve these constraints and produce new architectures.

fn. 1 Protzen JP., 1985: Inca Quarrying and Stonecutting. *Journal of the Society of Architectural Historians XLIV;* 2: pp. 161-182.

fn. 2 One of the most poignant commentators on this condition is Mario Carpo in his seminal text *The Alphabet and the Algorithm,* MIT Press, 2011.

Cyclopean Cannibalism, Matter Design & Quarra Stone, Seoul Biennial of Architecture and Urbanism: Imminent Commons, 2017

Cyclopean Cannibalism, Matter Design & Quarra Stone, Seoul Biennial of Architecture and Urbanism: Imminent Commons, 2017



A detail from *Inka Roca* in Cusco Peru, Cyclopean Cannibalism, Matter Design & Quarra Stone, Seoul Biennial of Architecture and Urbanism: Imminent Commons, 2017

Image of the assembly process, Cyclopean Cannibalism, Matter Design & Quarra Stone, Seoul Biennial of Architecture and Urbanism: Imminent Commons, 2017

Coursing sequence diagram, deciphered from Inka Roca, Cusco Peru, Cyclopean Cannibalism, Matter Design & Quarra Stone, Seoul Biennial of Architecture and Urbanism: Imminent Commons, 2017

Elytra Filament Pavilion, 2016
Achim Menges with Moritz Dörstelmann (ICD Stuttgart), Jan Knippers (ITKE Stuttgart) and Thomas Auer (Transsolar Climate Engineering, Stuttgart)

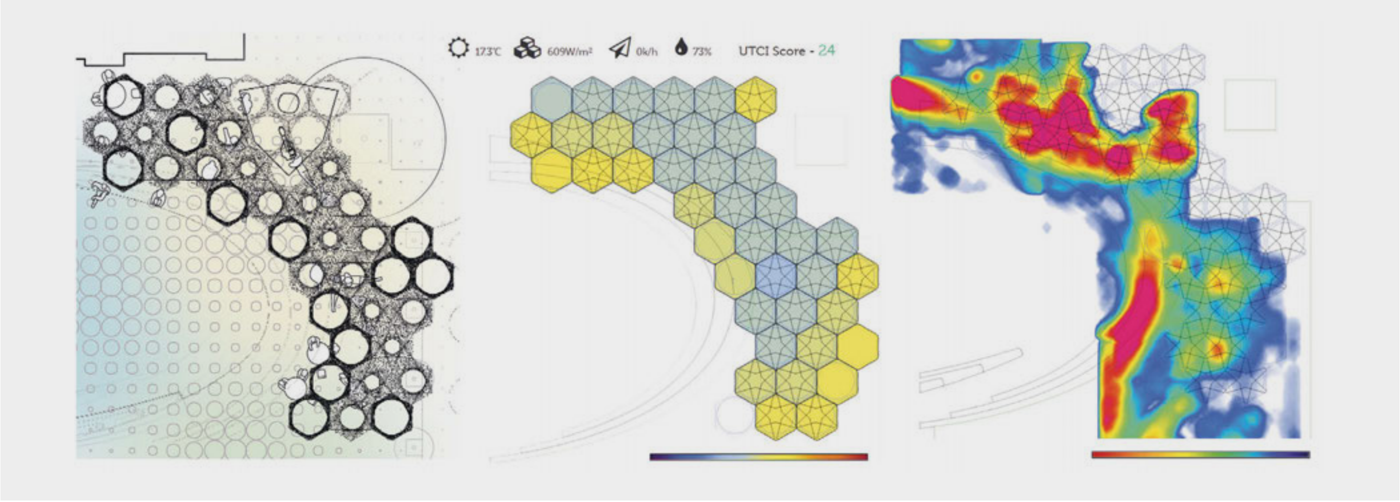
The Elytra Filament Pavilion demonstrates how architectural design can emerge from the synergising of the environment, material systems and production methods. The pavilion, built in 2016 as the centrepiece of the Victoria and Albert Museum's Engineering Season, was inspired by lightweight construction principles found in nature. It speculates on how the so-called fourth industrial revolution of robotics and cyber-physical production systems can enable the emergence of new structural and material systems, and therefore demonstrates the impact of digital technologies on our conceptualisation of design, engineering and production. It envisions an architecture in which the conventionally separate phases of design, production and use begin to blur in a continuous, feedback-driven process of (re)configuration and (de)construction of space during, and in response to its inhabitation.

The fibrous composite structure of the installation consists of two basic cells – the canopy cells and the column cells – made from the same load-bearing fibre material: transparent glass fibres and black carbon fibres. The production method reduces waste to a minimum by using an innovative robotic winding process. To make each cell, a robot winds resin-saturated glass and carbon fibres onto a rotating hexagonal winding tool. In this process, the transparent glass fibres form a spatial scaffold onto which the primarily structural black carbon fibres are applied. Once the robotic fabrication is complete, the composite material hardens and the winding tool can be taken out and reused.

The design, engineering and production of the installation's fibrous system is based on a continuous feedback loop between design, structural analysis and adaptation of each cell, resulting in an expressive, yet highly material efficient and exceptionally light structure, which weighs just 9 kg/m². The installation exploits the lightweight system and capitalises on the compactness and universality of robotic fabrication as a model for on-site manufacturing without a predetermined final state of design or construction. The canopy was equipped with fibre-optic sensors that allow for real-time sensing and monitoring of the forces within the structure. Changes to the structural systems caused by the further growth and adaptation of the canopy are driven by both the measurement of environmental parameters and anonymous data collected on how visitors inhabit the canopy space as captured by thermal imaging sensors. The canopy is therefore a learning robotic system, an evolving structure that is reconfigured over the time of the exhibition, exposing its impact on the behaviour of the garden's visitors and their preferred places to walk, stroll, rest or meet.

Elytra Filament Pavilion, Victoria and Albert Museum, London © Studio NAARO

Elytra Filament Pavilion construction © Victoria and Albert Museum, London



Sensor integration, Elytra Filament Pavilion © ICD & ITKE University Stuttgart

In process, Elytra Filament Pavilion © ICD & ITKE University Stuttgart

Chapter 2
Print

Chapter 2
Print

In this chapter, we will see how additive manufacturing technologies have embodied the ongoing shift from material being conceived of as analogue to being understood as inherently digital. In the previous chapter, we looked at ways in which robotic technologies have been used to replicate actions traditionally done by the artisan craftsman: picking up, placing, carving, weaving. In some cases, these technologies were used to combine the capabilities of many humans into a complex, crafted choreography between material and robot. For the most part in those examples, material is not treated as being digital – it remains analogue. However, the shift towards material as digital coincides with technological advancements in computing and fabrication as well as the rapidly increased accessibility of these tools. Additive manufacturing technologies have enabled architects and designers to create architectures that are far beyond the capacity of the architect as a craftsman, and that as a result surprise and astonish us with complex forms which could never previously be produced. The three projects contributions in this chapter, Space-Truss Prototype (2012) by Philippe Morel (EZCT Architecture and Design Research, and formerly of XtreeE), Digital Grotesque II (2017) by Michael Hansmeyer and Benjamin Dillenburger (Chair for Digital Building Technologies, ETH Zurich) and Thallus (2017) by ZHCODE at Zaha Hadid Architects with Ai Build and Odico Formwork Robotics, each innovates on existing additive manufacturing technologies – from extrusion to binder jetting – and do so by combining these technologies alongside other manufacturing processes, such as moulding and casting. Each of the projects recalibrate the way we think about what architecture is made of, from the parts and elements that make up a building to the constitution of an architectural element's materiality as well as the methods and economy of production. Or, put in other terms repeated elsewhere in this book and in our work as a lab, we see these projects contributing to a rethinking of what constitutes architecture, from how things are made, to the scale, networks and site of the 21st century factory.

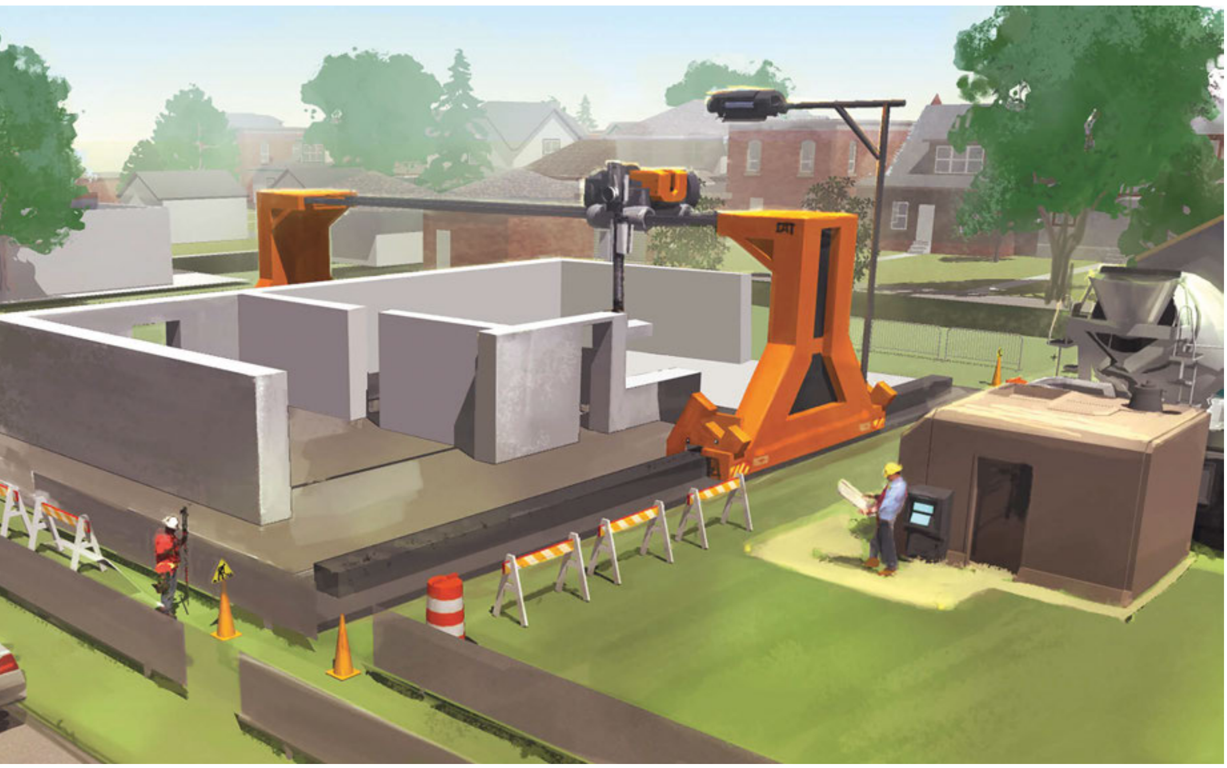
Things That Make Things

At the time of writing, it has been just over ten years since RepRap's first open-source, self-replicating desktop 3D printer, named Darwin, was released in 2008. [fn. 1] But the ideas behind 3D printing technology were not new. Attempts to make physical (and thus material) objects using only digital data have been around for the better part of the 20th century, since early attempts in the 1960s to produce 3D objects using lasers, and in

Smart Slab, DBT, ETH, DFAB House, NEST Building, 2018

May 1980 Hideo Kodama of the Nagoya Municipal Research Institute filed a patent for the first laser rapid-prototyping system using photopolymers. fn. 2 The invention of stereolithography by Charles Hull in 1984 meant that designs could be prototyped for the first time without having to go through a complex manufacturing process, while another MIT professor, Emanuel Sachs, coined the term "three-dimensional printing" in a patent filed in 1989. fn. 3 These developments mean that the production chains for design innovation were able to be shortened dramatically. fn. 4 Designs could be tested and prototyped at a rate never experienced before – almost instantaneously – and without having to rely on a huge amount of specialist knowledge of materials and manufacturing processes to produce prototypes and products. More specifically, additive manufacturing technologies have displaced historical constraints in manufacturing around geometric complexity, precision, the assembly of parts, material resources and the mobility of manufacturing technologies. Additive manufacturing enables efficient use of materials, reducing waste while allowing formal variability. It implies a short production chain, as it relies on the local materialisation of digital data, avoiding shipping and assembling multiple parts into a final product.

When considering the progress of additive manufacturing with robots, we see three approaches that use automated technology becoming prevalent in the 1990s and early 2000s, as it became more widely accessible and embedded into architectural production. An initial approach to scale up 3D printing processes was contour crafting, fn. 5 a method developed by Professor Behrokh Khoshnevis at the University of South California. Khoshnevis recently announced in 2018 that the Contour Crafting Corporation had been awarded a United States Department of Defense contract, a radical step which will likely have huge consequences for 3D printing in the US. fn. 6 This method proposes a 3-axis gantry-like structure carrying a concrete extruder. Also using a gantry, Italian entrepreneur Enrico Dini developed D-Shape, a large 3D printer using binder-jetting in a layer-by-layer printing process to bind sand, creating stone-like objects. More recently, construction companies such as Winsun fn. 7 or HuaShang Tenda fn. 8 are utilising large-scale 3D printing technology in combination with gantries for commercial developments. By bringing



Contour crafting, Behrokh Khoshnevis, University of Southern California

3D printing technology on-site, these methods reduce the production chain dramatically: potentially only material from the site is used to then "extrude" a building in one operation. There is no need to use hundreds of task-specific machines or shipping parts between manufacturers for final assembly. One machine, delivered in one initial shipment, does it all. In many ways, this is the perfect and sensible form of automation, but the reality is that this has proven difficult, mainly due to the large number of different parts and materials in buildings, which in their current form require differentiated procedures and machines to be automated. Furthermore, the fluctuant environmental conditions on a building site drastically affect the printing process, which often requires a highly controlled environment.

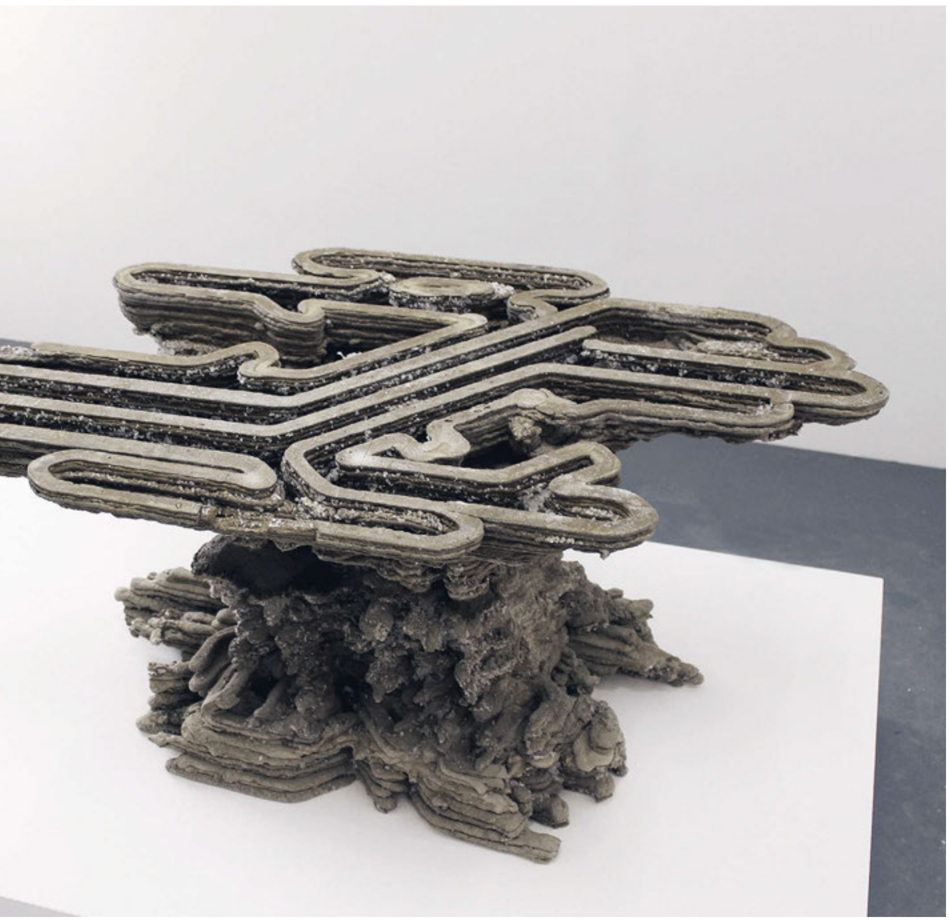
With the popularisation of industrial robots in architectural research, another approach using robots for 3D printing, rather than creating large-scale machines, started to emerge. Projects such as Mesh Mould (2012–14) by Gramazio Kohler Research at ETH Zurich fn. 9 allow for a greater flexibility than the 3-axis machines previously mentioned. The 6 axes of industrial robots allow greater geometrical freedom, although, the limited reach of the robot most commonly means that this method is used only in off-site manufacturing. In our lab, we have focused on spatial extrusion with robots and have argued for off-site manufacturing of 3D printed building elements with projects such as Voxatile (2016). fn. 10 Research conducted by Marta Malé-Alemany at IAAC was the first to focus on additive manufacturing using industrial robots to extrude clay layer by layer. fn. 11 Projects such as Mataerial (2013) at IAAC later explored the spatial extrusion of a ceramic polymer. fn. 12 Scale limitations make this process suitable for the creation of furniture and medium-scale products. The Dutch designer Dirk Vander Kooij developed Endless Chair in 2010, making use of a large format extruder that worked with recycled plastic. fn. 13 More recently, the Spanish design brand Nagami launched a series of products featuring geometries based on non-uniform layer deposition. This is achieved using the six degrees of freedom in a robotic arm, allowing the rotation of the extruder in three dimensions. fn. 14

Robotic extrusion also allows for a linear variation of some of the material properties, since the composition and colourant of the polymer can be gradually changed in the hopper. Amalgamma (2016), a project in Design Computation Lab, has explored concrete printing with a support material. fn. 15 Although this technique has proven to be a successful strategy for the creation of building parts and small to medium-scale objects, the problem of the subsequent on-site assembly remains and it commonly lacks a robust automated strategy. A third approach, situated in between the two previous methods, aims to add an on-site strategy to the workflow by mounting the robot on a different platform, that being a 1-axis rail or a 3-axis gantry. The Dutch company Aectual, which focuses on 3D-printed flooring, uses this technique to extend the linear reach of the robot using a linear axis unit. This allows it to extrude a plastic framework to be filled with terrazzo. fn. 16 The Digital Construction Platform (2017), developed at The Mediated Matter Group at MIT, utilises a smaller robotic arm attached to a larger industrial robot arm that sits on a mobile platform. fn. 17 This approach renders how different machinery can be combined to allow for higher efficiency in on-site 3D printing.

As an alternative to robotic printing, architects such as EZCT Architecture and Design Research with XtreeE, and researchers such as Philippe Block and Benjamin Dillenburger at the National Centre of Competence in Research (NCCR) ETH Zurich have made extensive use of existing industrial machines, such as voxeljet's 3D printers. These machines bind sand at an ultra-high resolution. Block has used the sand as it is to develop a 3D-printed floor system (2017) that does not require reinforcement in order to become structurally stable. fn. 18 This is an extremely short production chain, straight from the 3D printer to the site. Dillenburger's Smart Slab (2018) for the NEST building of Empa and Eawag, on the other hand, uses the sand print as a formwork, which is subsequently sprayed with fibre-concrete. CNC-milled formwork is then added to form ribs, into which concrete is cast. Afterwards, all the formwork, including the sand print, is removed. fn. 19 While the slab is offering a compelling case of 3D-printed prefabrication, the production chain is not very short and requires a lot of different steps, materials and manual labour.

Things That Make Themselves (or help others to)

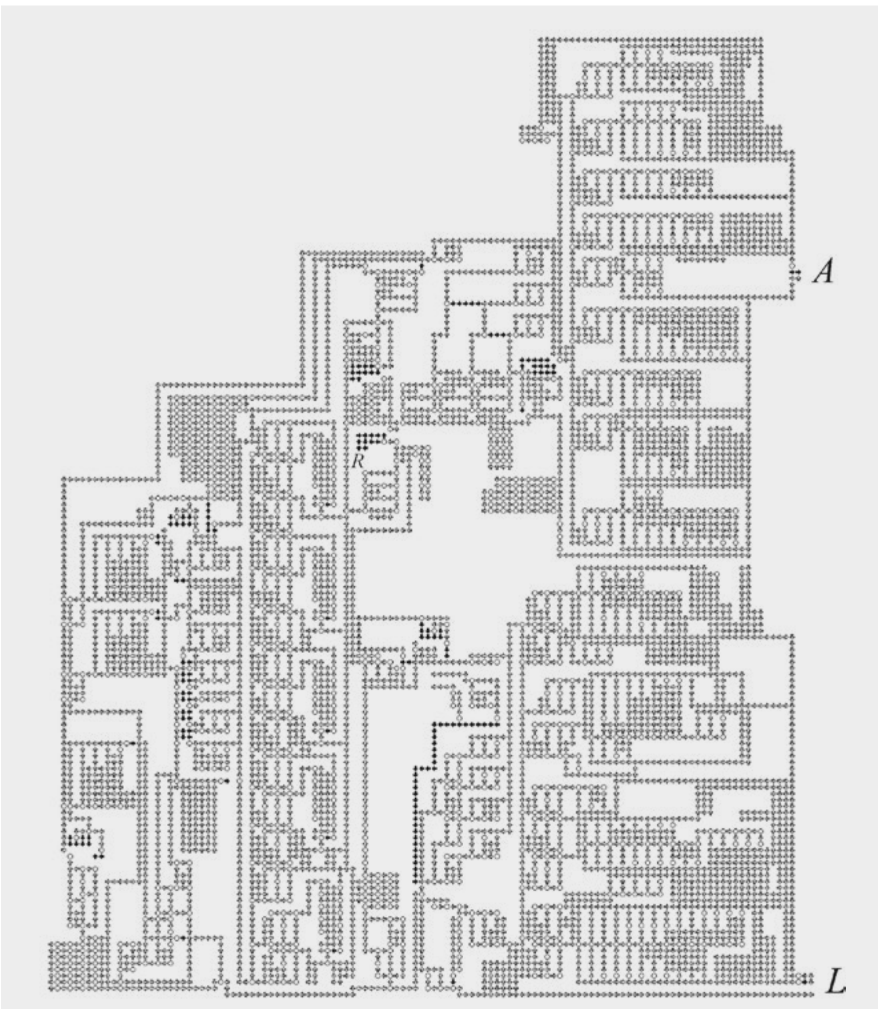
At first, additive manufacturing technologies were primarily developed for uses in manufacturing and medical research and product development, but this was followed by RepRap's 3D printing technology and the open-source blueprints for making it, which brought the seemingly infinite possibilities of 3D printing to both the specialist and the "everyday" maker interested in producing their own designs. About £250 would purchase the electronics and most basic parts to create a first-generation RepRap Darwin printer. fn. 20 The relatively low cost enabled the distribution of what used to be technology reserved for the corporate and academic elite into the everyday. This meant that there could be a greater degree of agility now on the side of companies and practices of all scales and sizes, as well as a recalibration of the role of the everyday consumer, as they could now print (almost) fn. 21 whatever they wanted. Designers could easily create, share and improve designs by engaging with a wider community of user-makers through frameworks such as the one RepRap was built on, where users were encouraged to make it their own through hacking and improving on its technology as required by their specific needs. Issues of democratisation, transferability and resolution of data, particularly around discourse and innovations in open-source frameworks and distributed manufacturing, were



Amalgama, Design Computation Lab, The Bartlett School of Architecture, UCL, 2015 to be enabled by this cultural shift away from an "ivory tower" model of knowledge production. As the RepRap was supposed to reproduce itself, it also enabled these users and makers not to have to be reliant (beyond the purchase of printable matter) on a consumer economy. This had the potential to be a revolution.

RepRap draws from the thinking behind John von Neumann's Universal Constructor (designed 1940s, published 1966): a self-replicating machine. In the Universal Constructor, von Neumann invented the notion of cellular automata to define the environment in which a self-replicating machine could be created. The Universal Constructor was to be made of three distinct parts: a set of instructions, a copy mechanism that can copy these instructions (or any instructions) and a control mechanism, which essentially would initiate the process and supply the set of instructions to the copy mechanism. fn. 22 RepRap tries to instrumentalise a very similar process: the blueprint is provided. But it fails in that the technology of today does not allow electronics – the basic mechanism to actutate a von Neumann-like process – to be printed.

Later in this book, we will see that a different approach to self-replicating assembly machines, informed by the work of Neil Gershenfeld and researchers at The Center for Bits and Atoms (CBA) at the Massachusetts Institute of Technology, can embed greater functionality into an automated assembler. The RepRap project, while it aims to be a von Neumann-esque Universal Constructor, gets caught in the catch-22 of 3D printing: 3D printed objects are inevitably static and unchangeable. Furthermore, the idea that a RepRap could be located in every home, office and research laboratory around the world was one that did not anticipate the issue of accessibility. The work of Nadya Peek at CBA is particularly relevant here however, where she recognises that machines that can make other machines need to be accessible, changeable and adaptable. fn. 23 Her critique of the fab lab is built on extensive experience in this area, where she observed that the tools used to make machines need to become more accessible in order for the fab lab to transcend from the specialist or professional tinkerer to the wider public. fn. 24 Potentially this work could one day result in the ultimate robotic dream: the best



Universal constructor with 32 states, Nobili and Pesavento, 1995 system of production humans can invent, one machine that can make everything, including itself.

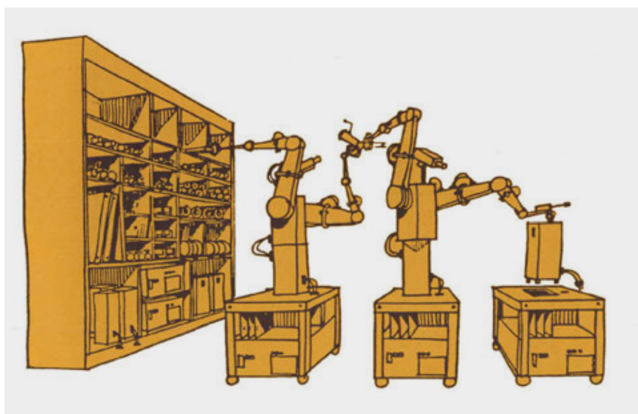
A Note on Mega Platforms

3D printing in architectural production has the potential to fulfil the requirements of a fully-automated society. It achieves a short production chain and, by removing the need to assemble thousands of parts, it has the potential to be radically cheap due to substantial savings on labour. Post-capitalist thinkers such as Nick Srnicek, Alex Williams, Paul Mason, Adam Greenfield and Peter Frase [fn. 25] regularly mention 3D printing as the ultimate fully automated technology: a mini-factory that is hyper-accessible to the masses. Jeremy Rifkin has also theorised the economic potential of 3D printing in The Zero Marginal Cost Society (2014), writing that with 3D printing technology, "anyone in the world can become a prosumer, producing his or her own products for use or sharing." [fn. 26] However these authors generally – Greenfield is an exception – do not engage with the material and technical constraints of a fully decentralised, networked world of production based on 3D printing. These include the lack of accessibility as highlighted by Peek above. Instead, these authors tend to treat 3D printing like the Universal Constructor.

The consequences of this vision, as Greenfield has observed, are vast for the current state of a capitalist economy, shifting us from a supply-and-demand economy to a "command economy", where objects are made as and when they are required. [fn. 27] You no longer need big capital or global mega-corporations to produce and enable consumption, all you need is a mega-platform made of prosumers, found in the technology itself. This potentially has hugely positive consequences for the power of a consumer in a market, who would no longer have to rely on capitalist systems of consumption. Simultaneously, as Mario Carpo has speculated, this would enable us to imagine a world

> that in the near future the cost of servicing a network of very small, local hydro-electric generators, for example, could easily be devolved to local communities of prosumers who would take care of those installations as their [sic] tend to their living environment, on an almost voluntary, communal basis. [fn. 28]

This is a beautiful prosumerist dream, and one that sits starkly in opposition to the reality of decentralised production (as we discussed briefly in our introduction) by mega-corporations such as Uber or Amazon or Deliveroo. These companies are using decentralised production (the labour of the precarious masses) to create a mega-platform, one that completely monopolises the potential of the prosumer to have any power at all (although some, such as Deliveroo drivers, have been successful in at least getting their case for unionisation to the courts in places such as the UK). [fn. 29] In his book Platform Capitalism (2016), Nick Srnicek points out how huge initial capital investments allow platforms to become the only marketplace for decentralised production, thus preventing



Self replicating machines, NASA Conference Publication 2255, 1982 "for free" cooperative alternatives to compete. fn. 30 So, we ask, would it not it be better if this kind of mega-platform for production was owned and run by government or a large co-operative? At least in Western societies, this seems like the real opportunity for decentralised technologies like 3D printing – enabling the mega-platform to exist at the level of a new commons, rather than pirated away into backspaces and maker fairs.

The Factory as a Service

In the "print" or "extrude" approach, off-site manufacturing of parts becomes unavoidable due to the material, geometric and technological constraints of on-site printing. A factory environment becomes more promising in terms of control and possibility. However, we have the opportunity due to automation and robotic technologies to go beyond the standardised product factory setting of the mid-20th century. Precedents for this kind of model of the factory can be found in the work of architect-maker Jean Prouvé, who produced flat-pack, lightweight houses in France and then shipped them worldwide. fn. 31 Instead, it can be offered as a customised service, and its site can be located away from the centres of economic production to save on the cost of owning or renting land. The implications of this are not dissimilar to the fab lab promise that we have looked at elsewhere in this book and carry their own potential to create new economies.

Nagami Design is one such company using this model. Not dissimilar to the same model used by Ensamble Studio to produce the Cyclopean House (2015), Nagami is located in Avila, Spain, where land is cheap and it is easy to ship products all over the world. In this kind of decentralised model, the factory becomes networked with prosumers worldwide. It becomes a service that can print any product or building element.

No More Parts, Almost

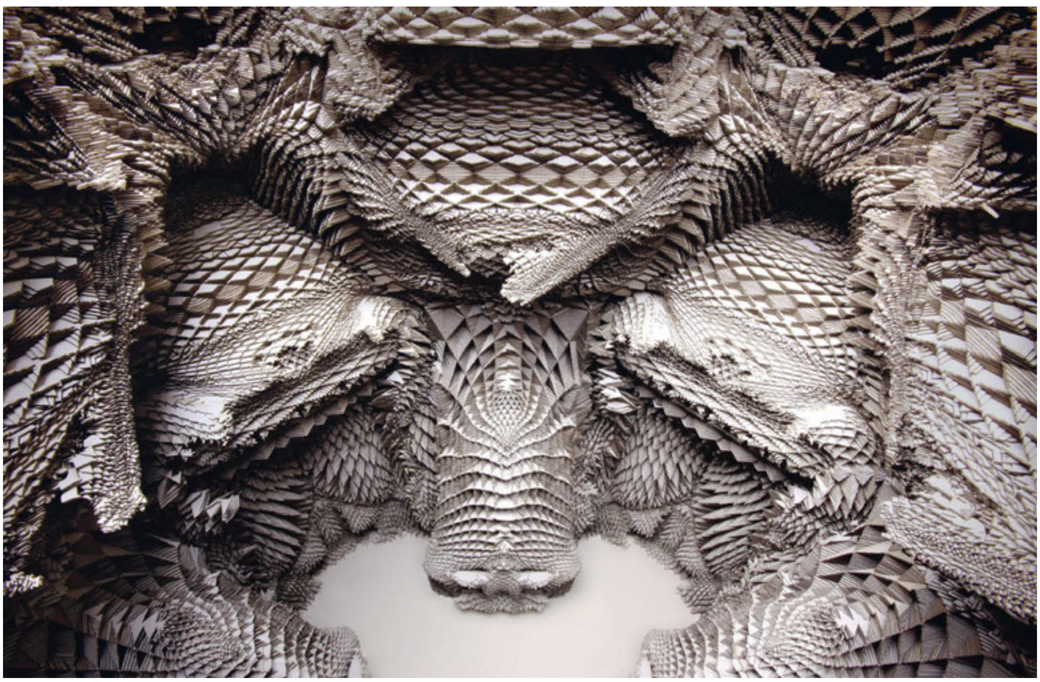
Architecture can be understood as a discipline that essentially develops knowledge about how to put small pieces together into a functional whole. As Daniel Köhler has adeptly written, drawing from the philosopher Bruno Latour, "architecture is about the many, the composition of a collective." fn. 32 A typical building is made of many, many parts – from nails to joists to membranes. Buildings have been designed more or less the same way since the Industrial Revolution, despite technology in other disciplines speeding ahead. As we discussed in the introduction and elsewhere, the translation of "digital design" and "digital fabrication" to "digital architecture" resulted in a hugely increased degree of building complexity, usually post-rationalised so that the way in which they were built was in a syntax that did not match the way in which they were designed. This dichotomy between design production and fabrication production gives us as architects ample opportunity to rethink the notion of part-to-whole relations in architecture: its mereology, fn. 33 or compositional constitution. This is perhaps the most important and relevant debate that we can have in relation to 3D printing and additive manufacturing. These technologies were embedded with a utopian idea of getting rid of the notion of the "part" in architecture as well as the notion of assembly: you should be able to print a building in one go. As Mario Carpo observed, the continuity and streamlined sinuousness of earlier "digital design" has shifted to be one of "excessive resolution" that is discrete and voxelised. fn. 34 With 3D printing, one could design with as little or as much complexity or resolution as required or wanted in terms of material and geometry, within the overall constraints of that material or geometric behaviour. And whether it was complex or simple would add very little, if not zero, cost to its production (which is itself very low).

The projects we have included in this chapter have realised the constraints of achieving this dream in different ways. Each of them has attempted to utilise the technology to do things that humans could never do with "craft-like" forms of labour and to go well beyond what had or has been already achieved. In this way, each of these projects is to a certain degree without precedent.

One of the largest concrete 3D-printed prototypes at the time it was produced, fn. 35 Space-Truss Prototype (2012) by Philippe Morel of EZCT Architecture & Design Research and XtreeE, was born out of some of the earliest research into the computational discretisation of architecture. As one of the projects that take on large-scale automation included in this book, the Space-Truss Prototype deals with the constraints of scaling up. 3D sand printing processes produced moulds used to make ultra-light high performance concrete structural lattices with hugely increased performance relative to other structural lattices. Here we see the micro-scale of material behaviour considered alongside structural loading paths and overall global geometry of the truss itself. This is very different to the smaller-scale slicing that occurs in other 3D printing processes where layers of material are deposited.

In the work Thallus (2017) by ZHCODE, Zaha Hadid Architects, Ai Build and Odico Formwork Robotics, we again see a mould being used, but instead of being used to create a path for material to self-consolidate, as in Space-Truss Prototype, a hot-wire shaped mould is used as formwork. An industrial robot deposits material onto this formwork, which is then rotated by another industrial robot to choreograph the printing. In a way, this process is not entirely dissimilar to the one used in the project Elytra Filament Pavilion in Chapter 1: Craft.

The geometric complexity in the work of Michael Hansmeyer and Benjamin Dillenburger in Digital Grotesque (2013) and the project featured here, Digital Grotesque II (2017), first came out of an investigation into rethinking a new order of the traditional column through subdivision: Subdivided Columns (2010). Here we see overarching topological and topographical data regarding form also conversing with data about how the columns were made: the subdivision determined not only the overall geometry but also the location of parts. However, this project was made out of layered CNC-milled or laser-cut parts – and therefore highlights the disconnection between design and fabrication. The fabrication process for the parts made the assembly process so complex that one can only imagine how much time it took to construct. For the Digital Grotesque series, Hansmeyer and Dillenburger instead utilised voxeljet sand printers that operate by



Subdivided Column, Michael Hansmeyer, 2010 gluing thousands of small particles of sand together. This is of course not humanly impossible, but very close to it – it is difficult to imagine how a human hand would have the precision and dedication to glue that many sand particles together. If it was produced by human labour, it would require a more “crafted” kind of approach utilising a different material. In a more crafted approach, material behaviour is of utmost importance: when it consolidates, how it deforms, its viscosity – these all drive the possibilities geometrically and syntactically.

This kind of “non-craft” form of 3D printing opens up interesting opportunities for architectural speculation. Material behaviour is almost irrelevant, it is contained and discretised. Particles are just fused with other particles. Building elements can be unfamiliar and thus unrelated to a disciplinary history. The parts that make up architecture are no longer bound by human labour. In this, they also begin to lose their ontological role, and assembly itself, while necessary, does not matter either.

fn. 1 https://reprap.org/wiki/RepRapOneDarwin#How_to_build_RepRap_1.0_.22Darwin.22

fn. 2 "Rapid Prototyping, Tooling and Manufacturing State of the Industry", Wohlers Report 2005, Wohler Associates, accessed: http://www.wohlersassociates.com/history.pdf.

fn. 3 https://patents.google.com/patent/US5204055A/en

fn. 4 Hod Lipson gives a great account of his first encounter with stereolithography technology in the late 1980s in his 2012 book with Melba Kurman titled *Fabricated: The New World of 3D Printing,* John Wiley and Sons, 2013, 8-10.

fn. 5 http://contourcrafting.com/

fn. 6 http://contourcrafting.com/rapid-response-construction-award/

fn. 7 Winsun, "Demonstrating the Viability of 3D printing at Construction Scale", World Economic Forum, case study report. https://futureofconstruction.org/case/winsun/.

fn. 8 Clare Scott, "Chinese Construction Company 3D Prints an Entire Two-Story House On-Site in 45 Days", *3DPrint.com,* 16 June 2016, accessed: https://3dprint.com/138664/huashang-tengda-3d-print-house/.

fn. 9 Norman Hack, Willi Viktor Lauer, Fabio Gramazio, Matthias Kohler, "Mesh Mould: Robotically Fabricated Metal Meshes as Concrete Formwork and Reinforcement", Ferro-11 and 3rd ICTRC conference, Aachen, Volume: 11, 2015.

fn. 10 "VoxaTile", *Towards a Robotic Architecture: Even when they do nothing, robots are evocative,* eds. Mahesh Daas and Andrew John Wit, ORO Editions, 2018, 132-135.

fn. 11 Marta Malé-Alemany and Jordi Portell, "FABbots: RESEARCH IN ADDITIVE MANUFACTURING FOR ARCHITECTURE", *Fabricate 2014: Negotiating Design & Making,* UCL Press, 2017, 206-215.

fn. 12 http://www.mataerial.com/

fn. 13 https://www.dirkvanderkooij.com/products/endless-chair-2010

fn. 14 https://www.nagami.design/

fn. 15 Manuel Jiménez García and Gilles Retsin, "Discrete Computational Methods for Robotic Additive Manufacturing", ACADIA conference proceedings, 2016.

fn. 16 Amy Frearson, "Robotic 3D printers create terrazzo floors in any pattern", *Dezeen,* January 2, 2018, accessed: https://www.dezeen.com/2018/01/02/aectual-robotic-3d-printers-terrazzo-floors-patterns/.

fn. 17 Steven J. Keating, Julian C. Leland, Levi Cai and Neri Oxman, "Towards Site-Specific and Self-Sufficient Robotic Fabrication on Architectural Scales", Science Robotics, Volume 2, Issue 5.

fn. 18 Philippe Block, Matthias Rippmann and Tom Van Mele, "Compressive assemblies: Bottom-up performance for a new form of construction", *Architectural Design,* Volume 87, Issue 4, Special issue: Autonomous Assembly: Designing for a New Era of Collective Construction, John Wiley and Sons, July/August 2017, 104-109.

fn. 19 Mania Aghaei Meibodi, Mathias Bernhard, Andreas Jima and Benjamin Dillenburger, "The Smart Takes From the Strong: 3D Printing Stay-in-Place Formwork for Concrete Slab Construction", *Fabricate 2017,* eds. Bob Sheil and Ruairi Glynn, UCL Press, 2017, 210-217.

fn. 20 https://reprap.org/wiki/Cost_Reduction

fn. 21 Neil Gershenfeld, "How to Make Almost Anything", *Foreign Affairs,* Volume 91, Number 6, November/December 2012, 43-57.

fn. 22 Joel Schiff, *Cellular Automata: A Discrete View of the World,* John Wiley and Sons, 2007, 2.

fn. 23 Nadya Peek, "Making Machines that Make: Object-Oriented Hardware Meets Object-Oriented Software", PhD dissertation, Massachusetts Institute of Technology, 2016, accessed https://dspace.mit.edu/bitstream/handle/1721.1/107578/974648092-MIT.pdf?sequence=1.

fn. 24 Ibid, 16.

fn. 25 See: Nick Srnicek, *Platform Capitalism,* 2017; Nick Srnicek and Alex Williams, *Inventing the Future: Postcapitalism and a World Without Work,* 2015; Paul Mason, *PostCapitalism: A Guide to Our Future,* 2015; Adam Greenfield, *Radical Technologies: The Design of Everyday Life,* 2017; Peter Frase, *Four Futures: Life After Capitalism,* Verso, 2016.

fn. 26 Jeremy Rifkin, *The Zero Marginal Cost Society,* St. Martin's Press, 2014, 89-108.

fn. 27 Adam Greenfield, *Radical Technologies: The Design of Everyday Life,* Verso, 2017, 89.

fn. 28 Mario Carpo, "Republics of Makers: From the Digital Commons to a Flat Marginal Cost Society", *Positions, e-flux architecture,* 30 January 2018, accessed: https://www.e-flux.com/architecture/positions/175265/republics-of-makers/.

fn. 29 Sarah Butler, "Deliveroo riders lose high court battle to gain union recognition", *The Guardian UK edition,* 5 December 2018, accessed: https://www.theguardian.com/business/2018/dec/05/deliveroo-riders-lose-high-court-battle-gain-union-recognition.

fn. 30 Nick Srnicek, *Platform Capitalism,* Polity Press, 2016, 42-43.

fn. 31 The work of Jean Prouvé has been documented widely, but one useful reference includes the book by Mimi Sheller, *Aluminium Dreams: The Making of Light Modernity,* 2014. This book demonstrates the impact material and technological innovation plus a globalising culture made on the regions that were, essentially, colonised by these technologies, both in terms of their political and environmental impact. For example, Prouvé's work was shipped mainly to Africa and we recognise the colonisation problem inherent in this.

fn. 32 Daniel Köhler, *The Mereological City: a reading of the works of Ludwig Hilberseimer,* Transcript, 2016, 7.

fn. 33 https://plato.stanford.edu/entries/mereology/

fn. 34 Mario Carpo, "Excessive Resolution: From Digital Streamlining to Computational Complexity", *Architectural Design,* Volume 86, Issue 6, Evoking Through Design: Contemporary Moods in Architecture, November/December 2016, 78-83.

fn. 35 Since 2012, XtreeE has continued to be a world leader in concrete 3D printing, as has Loughborough University in the UK, WinSun in China, Arup, IAAC in Barcelona and TU Eindhoven (this is not an exhaustive list).

fn. 36 Wes McGee, Jelle Feringa, Asbjørn Søndergaard, "Processes for an Architecture of Volume: Robotic Wire Cutting", *Rob | Arch* 2012: Robotic Fabrication in Architecture, Art and Design, 64.

Digital Grotesque II, 2017
Michael Hansmeyer and
Benjamin Dillenburger

The Digital Grotesque II project explores a new relationship between designer and computer, in which the computer turns from a passive instrument to an active partner that can expand the imagination of the designer. The computer learns how to generate architectural structures that evoke interest, curiosity and an emotional response. The resulting imaginary forms are brought to life as a six-tonne 3D-printed sandstone structure.

While today we can fabricate anything, design arguably appears confined by our instruments of design: we can design only what we can directly represent. If one looks at 3D-printed artefacts, there is often a discrepancy between the magic of digital fabrication and the conventionalism of the printed objects. What is needed is a new type of design instrument. We need tools for search and exploration, rather than simply control and execution. We require tools that go beyond the fulfilment or optimisation of simple functional requirements and that allow us to investigate and advance more ambiguous factors of the design: soft criteria. Soft design criteria such as aesthetic values are highly relevant for the interplay between humans and the built environment, as they influence the emotions that people feel through the architecture. These criteria are nearly impossible to quantify and to formulate as a set of rules or program. We have therefore sought to identify geometric properties of architectural form that can be measured and correlated with human perception and desirable emotions.

In Digital Grotesque II, instead of explicitly programming a set of predefined rules to reach these design criteria, the computer learns to calibrate the design with the goal of evoking stimulation and interesting the beholder. We trained the computer using design variations that had been evaluated online by hundreds of volunteers. The abstract geometric properties identified above are paired with statistical data measuring viewer preference, as quantified through number of views, viewing duration, sharing etc. Through this learning process, the computer constructs a model of the relationship between abstract geometric properties and human perception. The process functions without any architectural precedents and without direct control of the form. The computer program is able to actively design variations which are undrawable and unimaginable; which a human designer could not conceive of in their detail and differentiation. The role of the designer becomes one of a curator, steering the process and defining the appropriate design goals.

In the design process of Digital Grotesque II, the algorithm proposed thousands of design solutions optimised to evoke an emotional response in the beholder. In an iterative process, we learned about new design possibilities. We selected specific solutions and amalgamated them into a singular form. This new human-machine interaction frees the designer from thinking in terms of archetypes and categories, and ultimately serves to expand the designer's imagination and creativity. The resulting architecture is at once disorientating, intriguing and evocative, without being prescriptive. It inhabits a space between the natural and artificial, between order and chaos, offering unexpected moments of surprise.

Grotto interior view, installed at Centre Pompidou © Fabrice Dall'Anese

Printed components, © Jann Erhard

Printed components, © Jann Erhard

Grotto front view, installed at Centre Pompidou © Fabrice Dall'Anese

Grotto detail, © Michael Hansmeyer

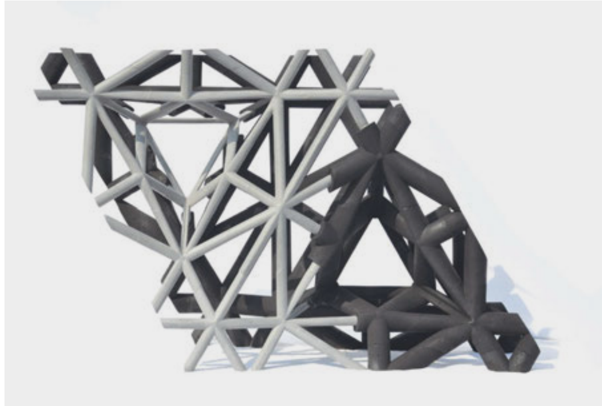
Grotto detail, Bottom Layer, © Michael Hansmeyer

Space-Truss Prototype, 2012
Philippe Morel, XtreeE & EZCT
Architecture & Design Research

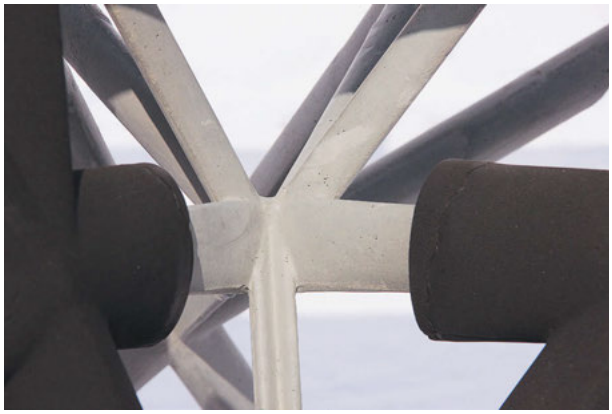
The work with UHPC (ultra-high-performance concrete) by EZCT Architecture & Design Research (EZCT) started 10 years ago, shortly after the development, in 2003, of voxel-based geometrical and structural experiments. The problem to be faced then was how to scale up discrete geometric models in order to address the real scale of architecture. A first approach involved creating self-interlocking elemental and universal building blocks ("u-Cube", standing for "Universal Cube for Discrete Construction" [in "Modelling Behaviour: Design Modelling Symposium 2015"]. The u-Cubes were hollow blocks designed to be combined to form a network of cavities that were later filled with self-compacting fibre-reinforced concrete.

After a first set of experiments, the project evolved towards multiple lattice models that were not solely based on hollow and universal construction blocks. Among the early multiple lattice model experiments in late 2010 were 3D-printed complex geometry moulds produced with a sand printer. These moulds, working at various sizes, allowed for many different variations and scales of each structural lattice model. This sand-based approach resulted in the production of the very first ultra-lightweight, three-dimensional UHPC lattice, which was presented at Archilab 2012 in Orléans, France. Nevertheless, notwithstanding the geometrical freedom intrinsic to this later approach, its main drawbacks were the dead weight of the moulds, the price of the printing process and the removal of the moulds, particularly when one wants to keep the concrete structure visible as well as achieve scalability.

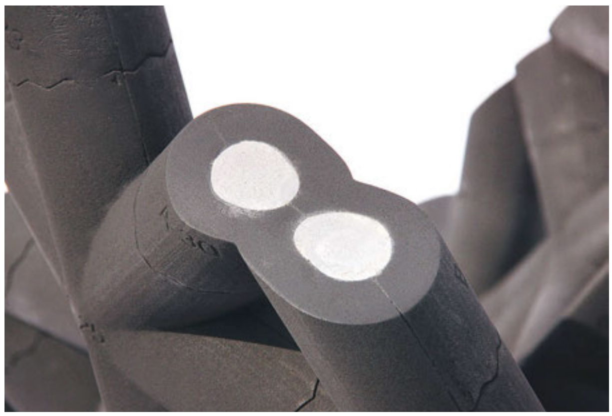
After experimenting with this technological approach in various environments, it became apparent that in order to address these issues, it would be best to create a start-up company entirely dedicated to large-scale 3D printing: XtreeE. As founding CEO, Morel supervised the realisation of the first fully functional complex geometry concrete structure in Aix-en-Provence in the south of France. The 4-metre high structure adhered to the principle of thin 3D-printed "tubes" filled with self-compacting UHPC already presented in Orléans with sand moulds. The project represents a completely new paradigm in the domain of concrete architecture and construction.



UHPC lattice in 3D printed sand mould 1:1 scale prototype, © XtreeE & EZCT Architecture & Design Research



UHPC lattice in 3D printed sand mould 1:1 Scale Prototype, © XtreeE & EZCT Architecture & Design Research



UHPC lattice in 3D printed sand mould 1:1 Scale Prototype, © XtreeE & EZCT Architecture & Design Research

Fully functional 3D printed sand, lost mould, © XtreeE & EZCT Architecture & Design Research

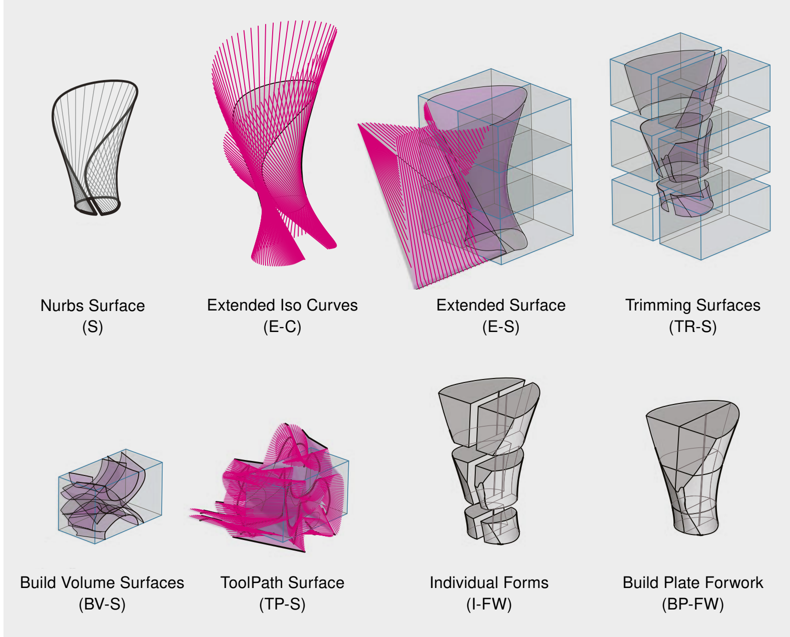
UHPC lattice detail 3D grid, © XtreeE & EZCT Architecture & Design Research

Thallus, 2017
ZHCODE, Zaha Hadid Architects,
Ai Build, Odico Formwork Robotics

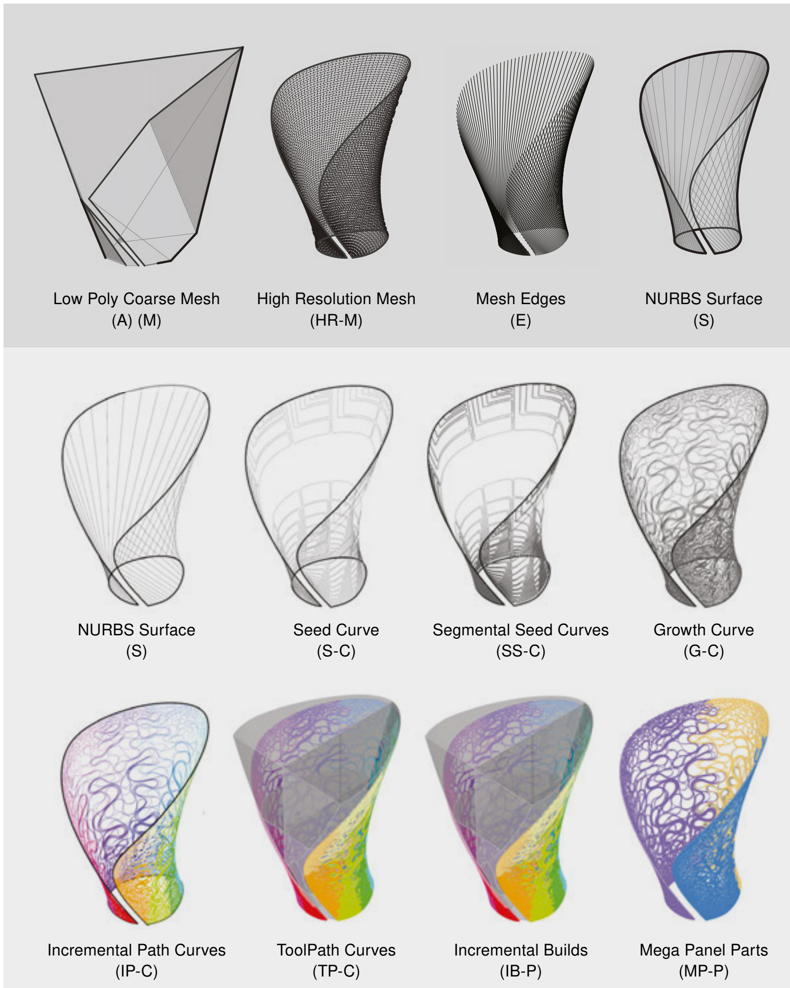
Through the investigation of form and pattern using state-of-the-art manufacturing and computational methods, Thallus celebrates the disciples of art, architecture and fashion. Thallus is made possible by automated additive manufacturing processes developed by Ai Build as well as robotic hot-wire cutting technology with Odico Formwork Robotics. It is an outcome of ZHCODE's ongoing collaborative research in digital design and manufacturing, and in the related universe of plausible geometries. Thallus is informed by the concept of ruled surfaces; a class of surfaces that are generated by the movement of a straight line in space around a given axis. The shape is a hyperboloid ruled surface to allow a hot, straight wire mounted on an industrial robot to cut the moulds. Material is then 3D-printed onto the moulds. Hot wire cutting offers an alternative method to traditional subtractive processing of solids and is done in a fraction of the time. This enables longer design periods and lower fabrication costs.

Thallus continues ZHCODE's interests in biological and physical processes, and the use of its computational abstraction to generate geometry. The design explores differential growth rates along a single, continuous seed curve. The curve "grows" in length, continuously adapting to the curvatures of a host surface while avoiding colliding with itself. The seed curve is iteratively edited such that the resulting pattern physically represents aspects of structural performance, manufacturing processes etc. The growth curve is used directly as the toolpath for additive manufacture and printed directly onto the moulds. The extreme lightness of the thermoplastic polylactic acid material is ballasted in place utilising a custom retention ring for temporary exhibition.

Thallus utilises physical simulation, digital simulation and constraints of robotic fabrication, developing a custom workflow that employs a computationally light coarse polygon representation of the geometry in order to develop the formworks, curve growth and robotic toolpath builds. The geometry incorporates feedback and revision arising from constraints of simulation, manufacture and assembly, enhancing the articulation of the fabrication-aware geometry.



Formwork production, Zaha Hadid Architects, AI Build, Odico Formwork Robotics



Procedural modeling of the conceptual geometry and procedural modeling of the additive manufacture geometry, Zaha Hadid Architects, AI Build, Odico Formwork Robotics

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Chapter 3
Assemble

Chapter 3
Assemble

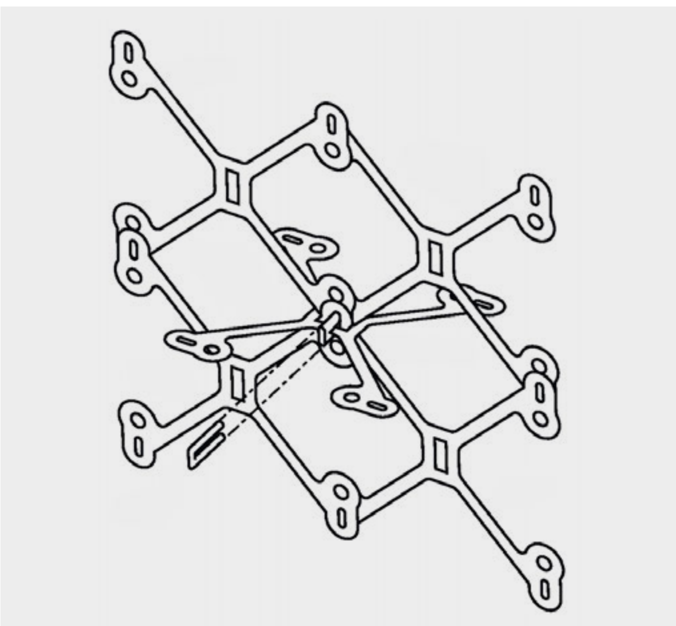
This chapter looks at the notion of assembly, or the act of putting together smaller parts in order to make larger parts or entire objects and, obviously, buildings. Robotic assembly is a process similar to that of the first chapter – Craft – but it starts to mix with notions of the second chapter – Print. The elements of architecture are calibrated for automated processes that work with materials not invented for human labour, but instead – as in the previous chapter – they are calibrated for use with robotic labour. Inherent to this is a critique of the way in which buildings are put together; buildings designed within earlier generations of "digital design" have been overly complex and inefficient in terms of their use of resources. Skylar Tibbits has referred to this as the "assembly problem" [fn. 1], while we have criticised it in our own work through what we have called a discrete approach to architecture. [fn. 2] As a way to deal with this problem, which is essentially a problem of how labour is used, the projects included in this chapter avoid overly complex movements by the robot as much as possible. The robot is then programmed to do the kind of repetitive, tedious actions that humans would not want to do or be able to do as effectively or efficiently. Indeed, the traditional syntax of architecture continues to fall away in this chapter. The notion of syntax, as we began to discuss in the previous chapter, becomes emphasised through the ways in which we organise part-to-whole relationships. Materials or particles are no longer crafted, moulded or printed into place (well, with one exception).

This chapter, along with Chapter 4: Many, is also one in which some of the arguments in our own work become most fully fledged, not least because it is a space for us to feature a project or two arising from Design Computation Lab. The three projects in this chapter, Voxel Chair 1.0 (2017) by Gilles Retsin and Manuel Jimenez Garcia (Design Computation Lab, The Bartlett School of Architecture), INT: Robotic Building Blocks (2016) by Zoey Tan, Claudia Tanskanen, Qianyi Li, Xiaolin Yin (Design Computation Lab, The Bartlett School of Architecture) and Rock Printing (2015–2018) by Gramazio Kohler Research, ETH Zurich, generally follow a kind of trajectory. This is one of the rare instances in the book where they can be charted along some kind of fuzzy line towards releasing architectural production from the constraints and limitations of human labour. The projects can be contextualised in several ways along this line: in their relationship to one another, their degrees of calibration towards robotic labour and the degree to which they enable the emergence of a new architectural syntax.

As a result, this is also a chapter where architectural precedents or a precise historical narrative or evolution in architecture are few and far between. In the last ten years, technological development has moved quickly, but as we argue throughout this book, architecture is at risk of being left behind unless it shifts quickly and more rigorously towards adopting automation and robotic labour. One such piece of evidence for this position is that the references that the projects in this chapter have tended to utilise are more interdisciplinary in nature than previous chapters. For example, this chapter develops the concept of digital materials developed by Neil Gershenfeld of the Center for Bits and Atoms at Massachusetts Institute of Technology. The notion of a material being digital – or, a digital material – was initially developed by Gershenfeld. [fn. 3] Many of the methods used in this chapter are additive, i.e. what is referred to often as "additive assembly", where there is a layering of parts on top of other parts, fixed by either the material or geometry of the parts themselves, joints, nails or string. This ensures that the reversibility required by the definition of digital materials fn. 4 is maintained. In addition, work on granular and jammed materials, such as the projects by Jaeger Lab at The University of Chicago, the work of Skylar Tibbits and the Self-Assembly Lab at MIT also informs this chapter. Jammed materials are structurally disordered, yet rigid and therefore structurally stable, and reversible. fn. 5

From the Digital to the Physical

As Gershenfeld has written, the term "digital fabrication" can be traced back to the 1952 creation at MIT of the first numerically controlled machine. fn. 6 In this moment, the connection was made between design and manufacturing. As Branko Kolarevic describes in his chapter "The (Risky) Craft of Digital Making" in the book *Manufacturing Material Effects: Rethinking Design and Making in Architecture* (2008), when digital fabrication tools are used by designers, the designer becomes a kind of "tinkerer" with the machine itself, experimenting on how to create the data used to manufacture their designs. fn. 7 This opens up a new economy of production. Kolarevic wrote about this in the context of what he referred to as digital "craft". This idea of the tinkerer is generally aligned with the artisan or craftsperson of Chapter 1. This approach towards assembly can be traced back in the majority of architectural experiments with robots: the emphasis is on the realisation of an overall complex form, from which elements are derived and then manufactured to later be assembled into the desired shape.



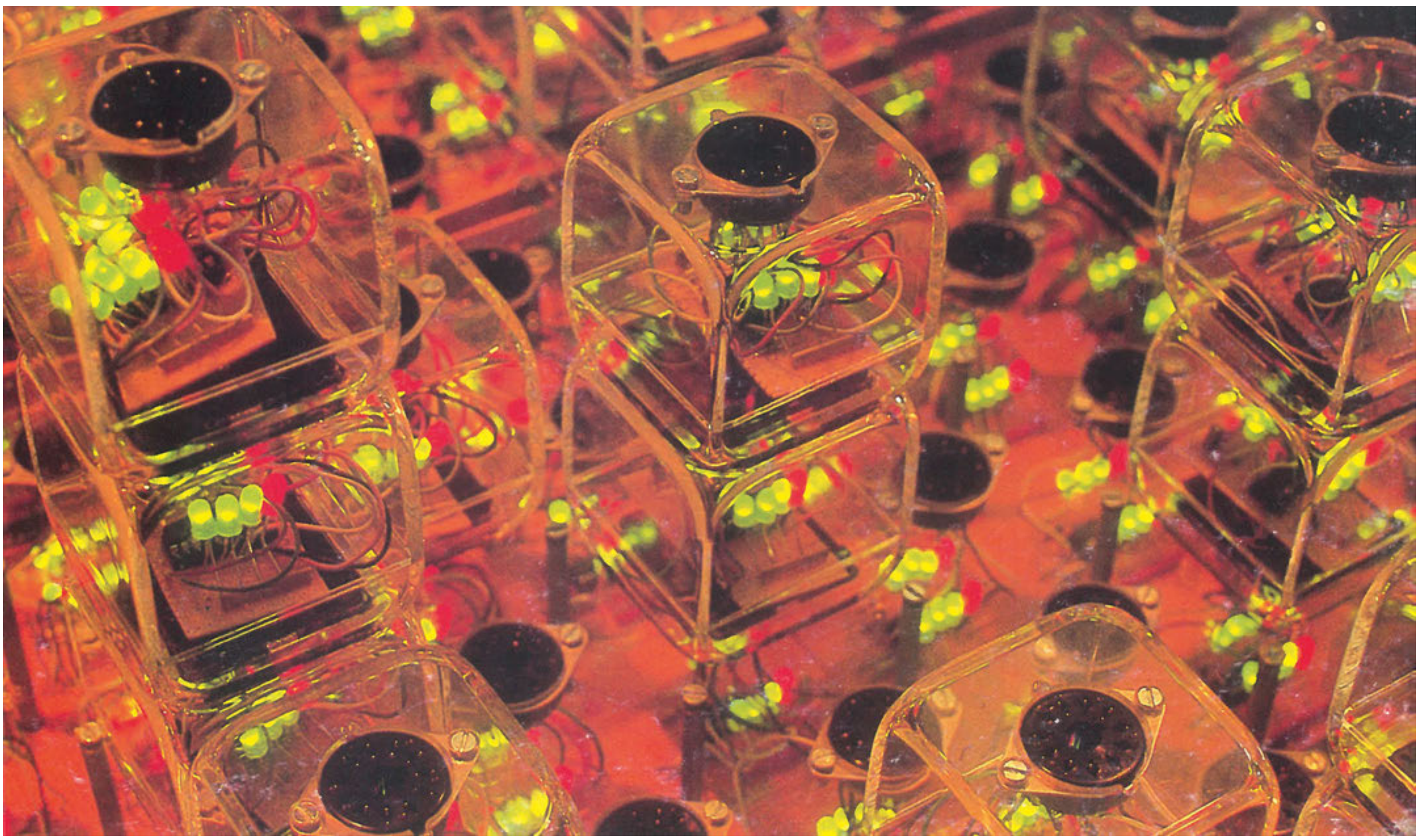
MIT CBO, Cheung et al., 2014

In one of the very first instances that we saw an industrial robot in architecture, the robot was assembling the undulating Programmed Wall (2006) by Gramazio Kohler Research at ETH Zurich. fn. 8 Still one of the most emblematic images of robots being used to produce architecture, the Programmed Wall showed how something so familiar and part of a global architectural culture – bricklaying (an artisanal form of labour) – could be automated, and with it also architectural production. In many ways the familiarity of the brick caused it to be so much more believable – much more than the CNC-milled surfaces, "blob"-like forms and Kolarevic's textured surfaces from the early digital experiments with digital fabrication. fn. 9 The blobby surfaces and patterns did not talk about automation at all, and as a result they did not seem like a threat to the core of architecture. Instead when adopted by practices and applied to projects around the world over the last ten to twenty years, the ribbed blobby NURBS surfaces resulted in buildings with a huge number of parts that were post-rationalised into compatibility with existing building methods. Despite a desire to reflect a particular political, social and cultural moment in time, therefore moving us from the digital-as-virtual to the digital-as-physical, these "digital" projects were merely adopted to an earlier paradigm of the physical, without transforming the way of thinking towards automation.

The Programmed Wall has suffered a similar fate, being thought of and written about as existing within the same paradigm of Kolarevic's digital craft. And rightly so. The project can be read as primarily exploring a new relationship with robotic machines – taking what had been possible in the digital realm for over a decade and making it physical. It was not focused on automation of architecture or of construction. The bricks do not have agency in determining the assembly of the wall itself. The design is predetermined, and the bricks are used to construct a continuous, parametrically defined surface. Their position is derived from an overall mathematical function – one of the tools in the repertoire of early digital designers.

The point of the wall is ultimately about differentiated form – the translation of an early digital project into a physical one. There exists a conceptual gap between the design and fabrication processes: a design is made, the data is then sent to the robot, and the robot executes the instructions from the design – there is no communication back through the process (as someone like Norbert Weiner and other cyberneticists would have argued for as we discussed in Chapter 1: Craft). This is the same gap that exists also in the previous chapter about 3D printing. There is a clear distinction between what is analogue and what is digital, what is physical and what is virtual. The assembly problem is clear: the labour in this project is still labour that could be done by a bricklayer, although probably more inefficiently and imprecisely.

Very different from this approach is the proposal by R&Sie(n) (comprised of Francois Roche, Stéphanie Lavaux and Jean Navvaro) for the FRAC Orléans courtyard in France in 2006 titled Olzweg. fn. 10 This project makes use of an industrial robot on a track assembling glass "bricks", suspending the gap between digital-as-virtual and digital-as-physical, redefining the notion of time, and the notion of what a "design" constitutes. The design is never finished; it is perpetually in a process



Universal Constructor, John & Julia Frazer, 1990 of modification. There is a blurriness and open-endedness to the building that we do not see in other works of this period. Here we see a building proposal that is designed for assembly with robotic labour.

Digital Materials: Matter as Data

Work at the MIT Center for Bits and Atoms by Neil Gershenfeld and others into digital materials suggests that matter and data can be combined to form a new kind of building block.

Gershenfeld and his collaborators defined a digital material as being "assembled from a discrete set of parts, reversibly joined in a discrete set of relative positions and orientations" and as having the same structure as data in a computer program. These discrete building blocks can then be organised into different positions, which can, in principle, be continuously altered. fn. 11 Digital materials by their very nature are able to transcend scales and platforms due to their (geometric, structural, material) abstraction as they can be compared to the children's toy Lego: every piece is programmed with a male-female connection, which is the equivalent of the 0 and 1 in digital data. fn. 12 This leads us towards the rethinking of how the act/actions of assembly and the combining of smaller parts together enable the emergence of effects, behaviours and qualities in the larger parts or objects. The gap between digital and analogue becomes diffused. There is no need to precompute a design as design decisions can be taken in real time, continuously, over and over again. Time is not limited to the length of a digital-as-virtual simulation. Data as digital materials or discrete building blocks can be assembled, removed, added and subtracted because of the way in which it can be structured to be in collaboration with robotic labour. This labour can respond to environmental and contextual changes and conditions.

This agenda is preceded by projects such as Generator Project (1978–1980) by Cedric Price, on which Julia and John Frazer collaborated, Fun Palace (1959–61) by Cedric Price in collaboration with the cyberneticist Gordon Pask, No-Stop City (1967) by Andrea Branzi, Nicholas Negroponte's SEEK (1969–70) and Julia & John Frazer's Universal Constructor (1990). Each of these projects utilised this idea of the translation of data or information into discrete building blocks using automated – and in some cases, robotic – architectural systems in a continuous state of assembly, disassembly and reassembly. In each project, there is an attempt to remove the difference between virtual information and the physical model, i.e. discrete data and discrete building elements are proposed as one and the same thing.

The Generator Project proposed a "system of cube-like elements that could be moved and combined with others or with additional elements" fn. 13, the arrangements of which were electronically linked together into a "vast working model – a gigantic reconfigurable array processor, where the configuration of the processor was directly related to the configuration it was modelling". fn. 14 In Fun Palace, a project written about at length by many scholars since its conception, an open-ended framework adapted continuously – via the movement of a robotic gantry hung from the ceiling – to the behaviour of its occupants, creating a symbiosis between building elements, technology and contextual conditions. This was proposed via an argument for a relationship between work and leisure which directly aligns itself with the proposals we see today by many left accelerationists (Srnicek, Williams etc). As Price wrote, "a new mentality is awakened during periods of self-willed activity" fn. 15 that would take place within the building. Branzi's polemic is different of course to Price's – and, markedly different from our own – for it views architecture itself as a harbinger of political ineffectiveness. Its critique is reliant on architecture's disappearance altogether. Instead, "human associations are ruled only by the logic of economy and rendered in terms of diagrams" [fn. 16], in an infinite, repetitive, non-differentiated and statistical space of consumption. In No-Stop City, the plan drawings are typed using a typewriter, but are also sequential, machinic, automated and assembled reconfigurable building environments.

In Negroponte's SEEK, gerbils played around with voxels (three-dimensional pixels [fn. 17]), which acted as a platform of communication between the rodents and a robotic arm which organises and reorganises the voxels. The rodents here are equitable to humans for their unpredictable nature, and SEEK demonstrates for us that robotic labour – here, the robotic machine that continually repositions the built environment for the rodents – needs to be used in order to "be responsive to changing, unpredictable, context-dependent human needs"; it requires an "artificial intelligence that can cope with complex contingencies in a sophisticated manner". [fn. 18] Negroponte highlights the very assembly problem we are addressing here in the shift from the digital-as-virtual to digital-as-physical, in that in SEEK there is a "substantial mismatch between the three-dimensional reality and the computer remembrances which reside in the memory of SEEK's computer." [fn. 19] The Universal Constructor was preceded by several earlier projects by the Frazers, such as a self-replicating computer (1979), a machine-readable grid board system (1990), machine-readable models as input devices (1980) and a three-dimensional intelligent modelling system (1980). Each of these earlier projects provide precedent for how physical models can be understood as data input devices, and required "one-to-one correspondence between the physical model and virtual model." [fn. 20] The Universal Constructor utilised cubes as physicalised voxels, embedded with data, and was therefore a very early architectural conception of a digital material.

Automated Additive Assembly

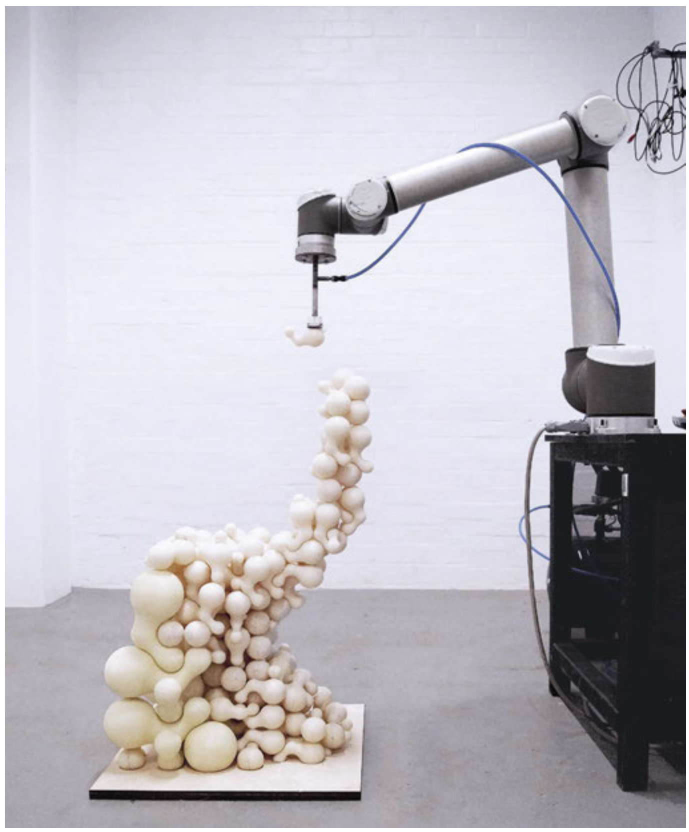
The universality and generic nature of the part (or voxel or data or building element) is designed in these projects to become part of the robotic or automated system. Importantly, they set a precedent for architectural building blocks that are not designed to be a "brick" (although the Frazers also designed a miniature brick – smaller than 2 sugar cubes!) [fn. 21] – made for human hands. We are looking instead at building blocks which have very little significance for human labour or assembly. So, what is a building part for a robot, then? And what does this change of what a part means for architecture itself? What happens when matter as data and digital materials, rather than overall form, becomes the driving issue for design? And what are the consequences if the role of the architect shifts from "not design[ing] a building or city as to catalyse them; to act that they may evolve?" [fn. 22]

We can look at work by Philippe Morel of EZCT Architecture and Design Research (Morel is also included elsewhere in this book) for one interpretation of some of the answers to only a few of these questions. Through an exploration of discrete algorithms, Morel produced the Computational Chair (2004), a digital-as-physical assembly of voxels. Although it is produced using non-discrete methods of manufacture, i.e. a CNC machine, the project is important for understanding the implications of automated assembly. It reaffirms the arguments of the earlier works by those mentioned above: it is about data, not geometry. There is not a mathematically-derived continuous surface. Instead there is a 3D data structure or voxel grid. fn. 23 The design process becomes automated, and so does production. There is no interest in materiality, the Computational Chair could be made out of CNC-machined timber, plastic or cast in concrete – it is generic and universal.

The question for assembly then is able to shift from the mass customisation of parts to mass customisation of the assembly. Parts are assigned a certain agency, be it data, form or behaviour, that is then negotiated through the assembly. This then enables the questioning of the role that robotic labour has in the process. There are several examples which, although varied, are emblematic of automated mass customisation of assembly. In The Sequential Roof (2010–2016) by Gramazio Kohler Research at ETH Zurich, timber struts are assembled together by a robot mounted on a huge, building-sized gantry. fn. 24 Here the production chain becomes a full-scale industrial process, demonstrating both the scalability and applicability of what has been realised at a smaller scale already. In the case of Bloom (2012) by Jose Sanchez and Alisa Andrasek, it is the interaction that the parts have with humans that is more important – rather than the robot. Parts have an internal geometric logic, setting out a specific vector, which can then be recombined into crowd-sourced structures. The building blocks establish a learning platform that allows people to realise the potential of their own labour. fn. 25 From a very different perspective, jammed material research from Jaeger Lab develops particles that exhibit the behaviour of sticking together, although with a very high entropy. fn. 26 Rather than using a robot, the Self-Assembly Lab from MIT looks into processes where parts assemble themselves into functional structures under external pressure. fn. 27

Morel's research also continues to be particularly poignant here when he further develops his research from the

Computational Chair, EZCT Architecture Design & Research, 2006

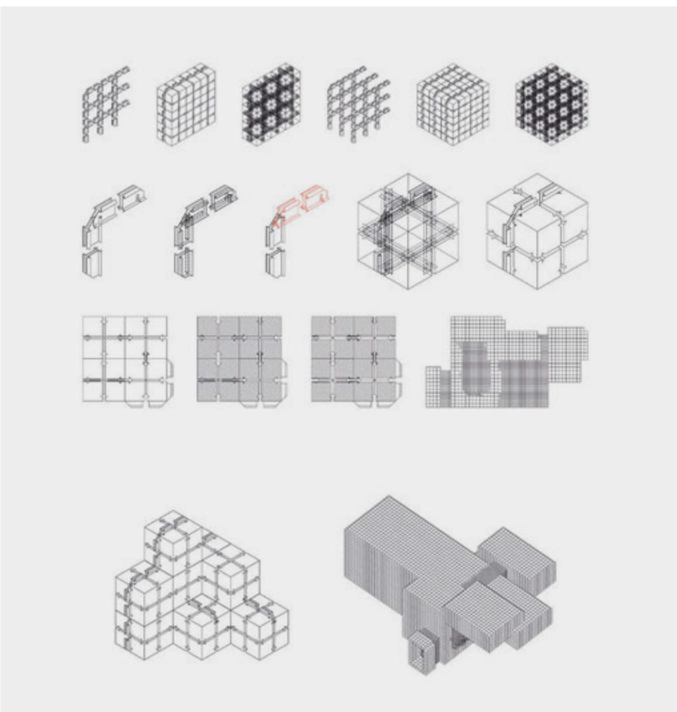


Mickey Matter, Research Clustter 4, Design Computation Lab, The Bartlett School of Architecture, UCL, 2016

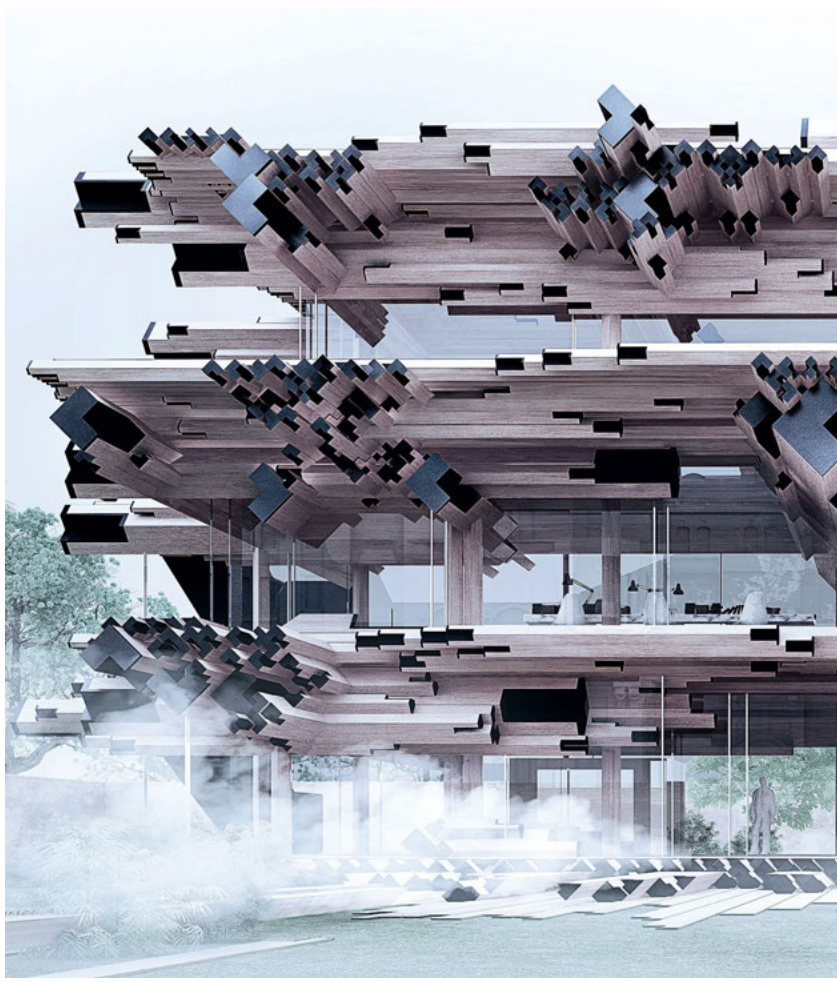
Computational Chair into physically discrete building elements. With the Universal House and Assembly Element (2009–12), he creates a foam building block with a predefined connection sequence. This block can be assembled with other foam blocks. An internal network connects the blocks, allowing concrete to be cast inside and form a continuous, load-bearing structure. The resultant architecture is something between Oswald Mathias Ungers' House Without Qualities (1995), Superstudio's Continuous Monument (1969) and the game Minecraft. For Morel, this is also the endpoint of architecture, the moment everything can be automated and the debate for architecture is over. [fn. 28] Although not specifically showing a robot, the Universal House is an example of a fully automated architecture.

New Architectural Syntaxes: The Discrete

The notion of the building block as both physical building material and bit of data – a discrete assembly – is crucial for building upon the notion of digital materials and additive assembly with robotic labour as a possible solution to the assembly problem. Architects can start speculating about architecture that also remains discrete in its physical form and that can also be automated, adapted and transformed. This new kind of architecture has an open-ended syntax where parts can be easily added or removed. There is no notion of an overarching form, instead we have wholes without parts. Architecturally, this is a move towards a non-geometrical, data-based architecture that consists only of the parts and their relations. In the Diamond House (2016) by Gilles Retsin, a complex, functional whole is achieved as an emergent property of the interaction of simple, serialised elements, that pre-exist the design. There is no distinction between structure and cladding, column or floor. There is instead an abstract, volumetric space, within which a discrete set of elements takes a position. [fn. 29] Mario Carpo has referred to the



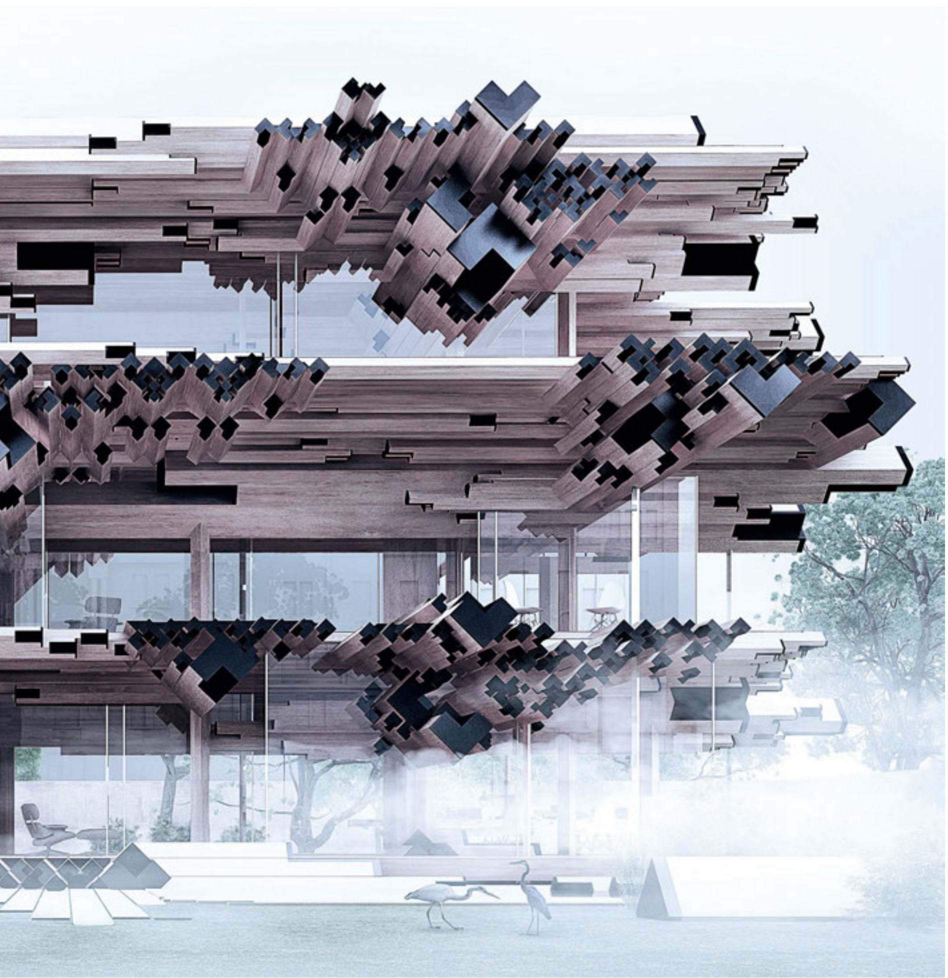
Universal House, Philippe Morel, 2009



Diamond House, Gilles Retsin Architecture, 2016 same abstraction in his now-canonical text "Breaking the Curve: Big Data and Design" in *Art Forum* (2014) as the discretisation of the spline curve. fn. 30 This moves architectural thinking much closer to the indexical architecture of No-Stop City than to the continuous surfaces of the early digital.

As a first full-size experiment of discrete assembly, the Tallinn Architecture Biennale Pavilion (2017) by Gilles Retsin tests a discrete assembly. An abstract fragment of a larger whole, the pavilion tests the design of discrete building blocks that act as large-scale digital materials. Off the shelf, standardised plywood sheets are CNC-milled into a kit of parts that can be combined into a lightweight building block, able to perform in a variety of loading conditions. Elements are not optimised to perform in a unique condition but respond through their iterative accumulation and recombination to different conditions. The elements can be cheaply mass-produced and enable an open system of design and production. Unlike a modernist assembly, these building blocks are not pre-defined, geometric types – like columns or slabs – that only operate for a specific function. And unlike a continuous, parametric design, these parts are not derived from a pre-defined whole, but pre-exist the design and are open-ended.

The question then is: what happens to architectural syntax when parts are designed for robotic assembly rather than human assembly? The project contributions included in this chapter highlight a development of ideas that provide possible clues to an answer for this question. The Voxel Chair 1.0 (2017) by Gilles Retsin and Manuel Jimenez Garcia with Vicente Soler (Design Computation Lab, The Bartlett School of Architecture) does not remove or add material to establish a form. Instead, the form is given – a thick, volumetric shape derived from a Panton Chair (1960) – and is then voxelised. Every voxel contains a toolpath fragment that is printable with an industrial robot. Subsequently, these discrete toolpath fragments are combined and assembled into a continuous kilometre-long toolpath. This approach is therefore different from the 3D printing we saw in Chapter 2, where the toolpath is generated from the overall form. In this case it's the assembly of the toolpath that is actively designed and defines the overall form. The overall form of the Panton Chair (1960) does not matter and is blurred. In terms of robotic assembly, this can be understood as the robot printing one part, and then assembling the next part, in one go. This project exists somewhere on the boundary of the shift digital-as-virtual and



digital-as-physical because its discreteness still resides in the virtual model. The implications of this method are tested further with the project INT: Robotic Building Blocks (2016) by Zoey Tan, Claudia Tanskanen, Qianyi Li, Xiaolin Yin (Design Computation Lab). This project speculates about the automated assembly of timber building blocks. Similar to SEEK, it proposes interaction with humans in the assembly process. If we compare this project to Voxel Chair and EZCT's Computational Chair, we have a project that is both digital in the virtual model and in the physical realisation. Syntactically it is always evolving and adapting, as the design is calculated at every individual moment throughout the assembly process through the interaction between robotic labour and human labour.

Rock Printing (2015–2018) by Gramazio Kohler Research, ETH Zurich puts this paradigm of assembly into question. It does not need custom-made, prefabricated building blocks either in the virtual or physical. Instead we have small rocks bound together with string. The exact placement of the two building elements does not matter. When the string is removed, the structure is disassembled and then can be reassembled again using the same materials. The low-tech nature, using raw everyday waste materials, and therefore accessibility of this process make it very suited to the current state of the industry – it requires little change. Here we see a project that takes a place at the other end of the spectrum to the Programmed Wall from 10 years prior in the Gramazio Kohler Research trajectory. Rock Printing is not about overall form or ascribed meaning or values, nor is it about parametric relationships, but about very abstract part relations and behaviours.

The move to a world of robotic assembly has not only architectural but also important social and political consequences. Compared to the two previous chapters, the move to a world of digital assemblies, and specifically to a world of discreteness, enables a degree of engagement with affordability and accessibility. The part is seen as something that both reduces labour on site, but also as something that makes things accessible – either economically or in terms of interaction, communication and interfacing with people. This is a big difference compared with the approaches in the first two chapters of this book. The emphasis here is much more on automation to provide an alternative solution to the assembly problem, and on this substantial rethinking of the way we develop frameworks for labour and production, and less on the agenda of differentiation, variation or articulation set out previously in earlier generations of the digital.

fn. 1 Skylar Tibbits, “From Automated to Autonomous Assembly”, *Architectural Design,* Volume 87, Issue 4, Autonomous Assembly: Designing for a New Era of Collective Construction, July/August 2017, 8.

fn. 2 *Architectural Design,* Discrete: Reappraising the Digital in Architecture, Vol 89, Issue 2, ed. Gilles Retsin, April 2019.

fn. 3 Neil Gershenfeld, “How to Make Almost Anything”, *Foreign Affairs,* Volume 91, Number 6, November/December 2012, 51.

fn. 4 George Popescu and Neil Gershenfeld, “Digital Materials”, 2019, 3, accessed: https://www.researchgate.net/publication/228430160_Digital_Materials.

fn. 5 Andrea J. Liu and Sidney R. Nagel, “Granular and Jammed Materials”, Soft Matter, 2010, 6, accessed: https://pubs.rsc.org/en/content/articlehtml/2010/sm/c005388k.

fn. 6 Neil Gershenfeld, “How to Make Almost Anything: The Digital Fabrication Revolution”, Foreign Affairs, November/December 2012, Volume 91, Number 6, 43.

fn. 7 Branko Kolarevic, “The (Risky) Craft of Digital Making”, *Manufacturing Material Effects: Rethinking Design and Making in Architecture*, eds. Brando Kolarevic and Kevin Klinger, Routledge, 2008, 123-124.

fn. 8 A continuation of this project applied at the scale of a building can be seen in Chi-She (2016) by Archi-Union Architects led by Philip Yuan, featured in Chapter 1: Craft.

fn. 9 These experiments include projects such as those by Greg Lynn’s Embryological House (1998). Lynn’s Blob Wall (2006-2008), coincidentally was produced at the same time as the Programmed Wall by Gramazio Kohler Research.

fn. 10 We see this project again to help substantiate a different argument later in Chapter 5.

fn. 11 Neil Gershenfeld, Matthew Carney, Benjamin Jenett, Sam Calisch and Spencer Wilson, “Macrofabrication with Digital Materials: Robotic Assembly”, AD: Special Issue: Material Synthesis: Fusing the Physical and Computational, Vol. 85 (5). Wiley, 2015.

fn. 12 Ibid, 123.

fn. 13 Bevin Cline and Tina di Carlo, in Terence Riley, ed., *The Changing of the Avant-Garde: Visionary Architectural Drawings from the Howard Gilman Collection,* New York: The Museum of Modern Art, 2002, 156.

fn. 14 John Frazer, *An Evolutionary Architecture,* Architectural Association, 1995, 40-41.

fn. 15 Cedric Price and Joan Littlewood, “The Fun Palace”, *The Drama Review: TDR,* Vol. 12, No. 3, Architecture/Environment, Spring, 1968, 129.

fn. 16 Pier Vittorio Aureli, *The Possibility of an Absolute Architecture,* MIT Press, 2011, 20.

fn. 17 The concept of the voxel has been an important aspect of our work in developing discrete building blocks. For further elucidation and mapping of historical references on this topic see the recent book by Roberto Bottazzi *Digital Architecture Beyond Computers: Fragments of a Cultural History of Computational Design* (Bloomsbury, 2018), in particular the chapter “Voxels and Maxels” 177-205.

fn. 18 Nicholas Negroponte, “Semantics of Architecture Machines”, Architectural Forum, October 1970, 40.

fn. 19 Ibid.

fn. 20 John Frazer, An Evolutionary Architecture, Architectural Association, 1995, 37.

fn. 21 Ibid, 39.

fn. 22 Ibid, 7.

fn. 23 Philippe Morel, Valerian Amalric, Jelle Feringa, Felix Agid, “Studies on Optimisation: Computational Chair Design using Genetic Algorithms”, 2004, accessed: http://www.frac-centre.fr/gestion/archives/2009/biothing/pdf/b_EZCT.pdf.

fn. 24 Jan Willmann, Michael Knauss, Tobias Bonwetsch, Anna Aleksandra Apolinarska, Fabio Gramazio and Matthias Kohler, “Robotic timber construction - Expanding additive fabrication to new dimensions”, *Automation in Construction,* 61, 2016, 16-23.

fn. 25 Jose Sanche and Alisa Andrasek, “Bloom the Game”, ACADIA, Adaptive Architecture, conference proceedings, 2013, 403-404.

fn. 26 https://www.jaegerlab.com/

fn. 27 https://selfassemblylab.mit.edu/

fn. 28 Philippe Morel, “Sense and Sensibilia”, *Architectural Design,* Volume 81, Issue 4, Mathematics of Space, John Wiley and Sons, 122-129.

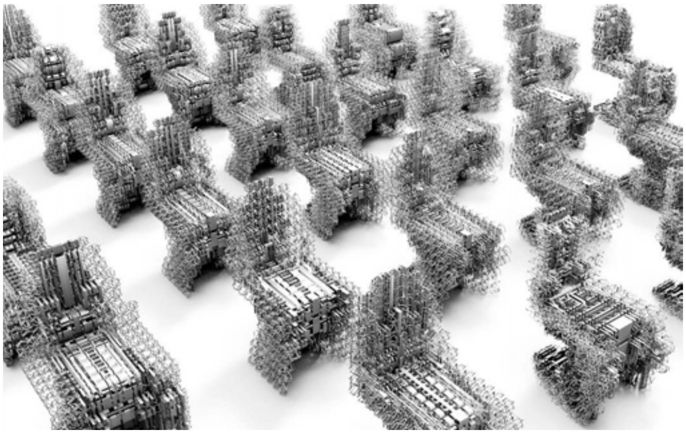
fn. 29 Gilles Retsin, “Discrete Assembly and Digital Materials in Architecture”, *FABRICATION | Robotics: Design & Assembling* - Volume 1 - eCAADe 34 conference proceedings, 143-151.

fn. 30 Mario Carpo, “Breaking the Curve: Big Data and Design”, *Art Forum,* February 2014, https://www.artforum.com/print/201402/breaking-the-curve--big-data-and-design-45013.

Voxel Chair 1.0, 2017
Manuel Jimenez Garcia and Gilles Retsin with Vicente Soler, Design Computation Lab, The Bartlett School of Architecture, UCL

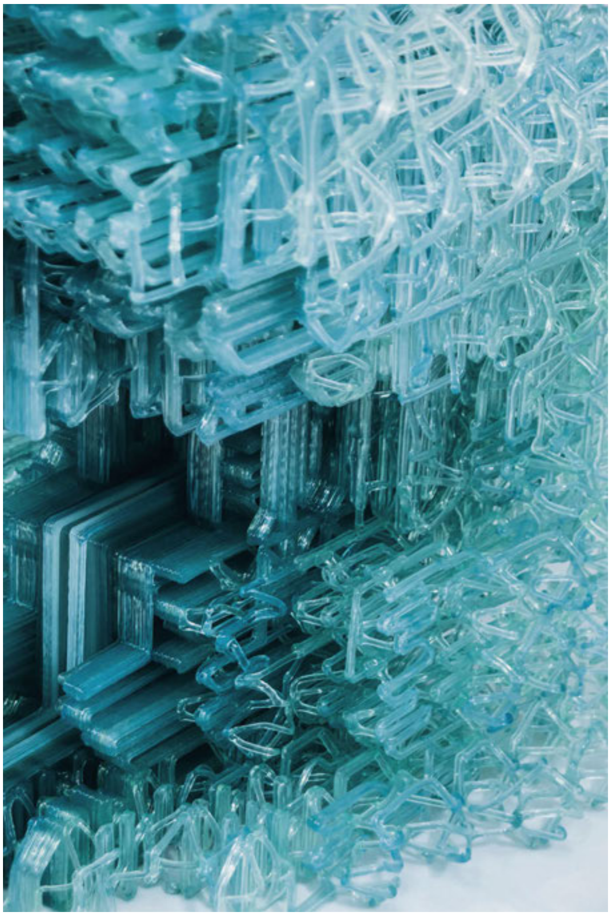
The Voxel Chair utilises new software developed specifically for robotic 3D printing. It was developed for the Imprimer le Monde (2017) exhibition at the Centre Pompidou in Paris, France, and recently became part of the museum's permanent collection. The Voxel Chair is based on research developed with students in Design Computation Lab (directed by Mollie Claypool, Manuel Jimenez Garcia, Gilles Retsin and Vicente Soler) in projects such as Amalgamma (2015) and CurVoxels (2015).
The software enables the design and control of thousands of fragments of lines that are combined together to constitute an object. These lines form one continuous line that can then be extruded by an industrial robot. The software is based on voxels, or 3-dimensional pixels, a technology which comes from the medical imaging industry. With traditional design software, designers define objects through modelling surfaces, but they are never able to design the constitution of the volume. The software allows designers to make decisions about every part of the object.
The iconic Panton Chair is used as a form to test the software because of how optimised it was for the fabrication systems of its time – the older manufacturing technique of using moulds, and because of its challenging cantilever. However, instead of being optimised for moulding, the Voxel Chair is optimised for robotic extrusion. Using meta-materials and topological optimisation for the first time with larger-scale objects, the approach enables designers to make objects that are much more intricate than other 3D-printed objects and can accurately portray their structural behaviour and functionality. This reflects the different requirements of designing for utilising robots – where the behaviour and properties of the material extruded dictate possibilities. Hence, areas that need to be strong are extruded with a very dense and intricate pattern, while areas that are there to be sat on have more flexible and looser patterns.

In the Voxel Chair, 2.36 km of toolpath is assembled into one continuous line. The chair was printed with a pellet extruder using raw plastic particles rather than filament. The plastic is PLA, a non-toxic, biodegradable plastic from renewable resources such as corn starch. The chair uses a transparent PLA, mixed with cyan-coloured particles, which results in a colour gradient. It was designed in London, and then printed in Avila, Spain at robotic manufacturing company Nagami. Voxel Chair developed the design method, software, user experience and robotic fabrication technologies, embodying a system of production that can allow for the generation of multiple objects, variations and material organisations.

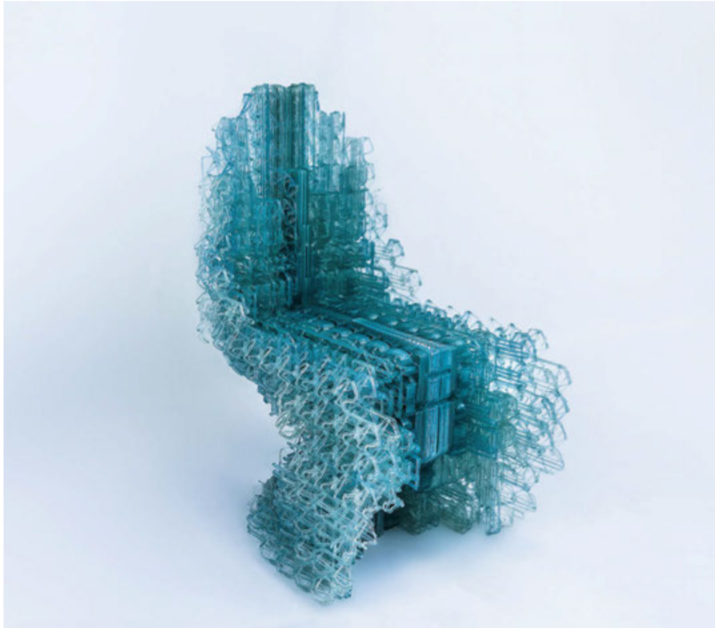


39+ chairs, Voxel Chair 1.0, Design Computation Lab, 2017

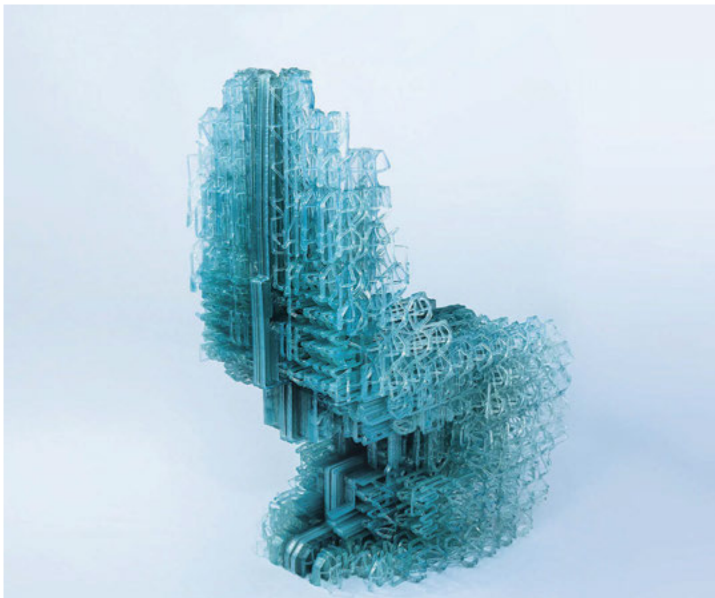
Discrete design software, Voxel Chair 1.0, Design Computation Lab, 2017



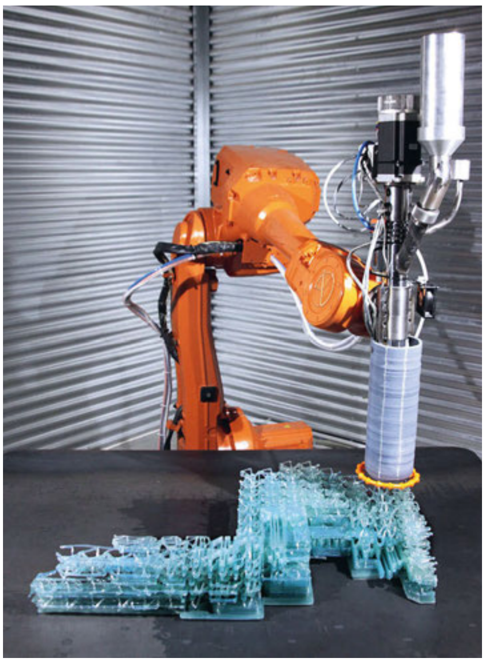
Detail, Voxel Chair 1.0, Design Computation Lab, 2017



Front, Voxel Chair 1.0, Design Computation Lab, 2017



Back, Voxel Chair 1.0, Design Computation Lab, 2017



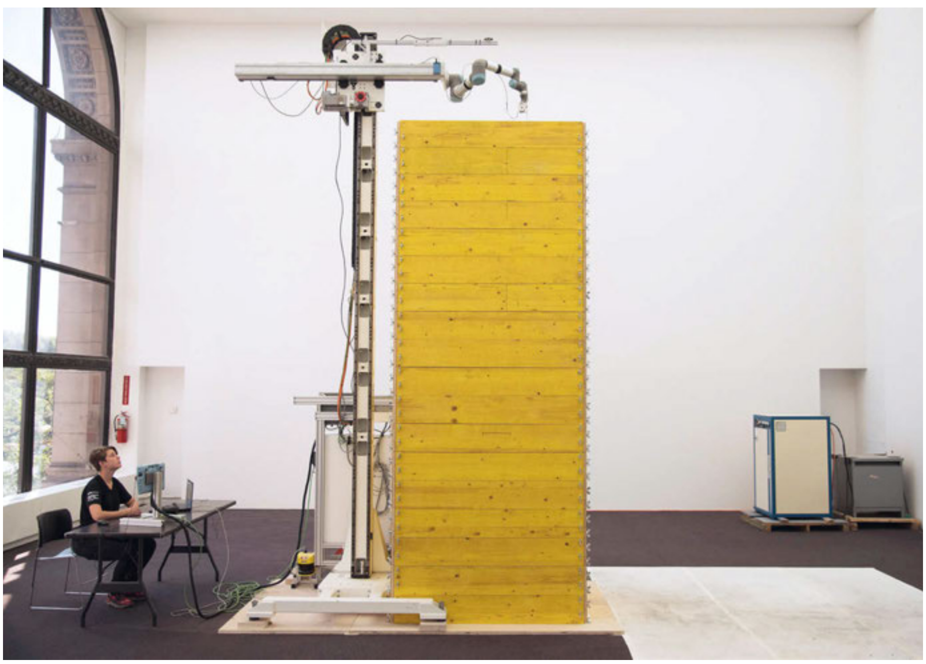
Robotic printing, Voxel Chair 1.0, Design Computation Lab, 2017

Rock Printing, 2015–2018
Gramazio Kohler Research, ETH Zurich

Rock Printing employs computational design and robotic fabrication to combine two mundane materials with opposite characteristics – gravel and string – into a powerful material system for sustainable construction. The material system exploits the physical phenomena of jamming, by which an aggregate medium switches from liquid to solid and vice versa depending on its confinement. This behaviour makes it possible to build architectural structures that are fully reversible and can be recycled or modified with minimal effort by rewinding the string onto spools.

In order to fabricate Rock Print structures, string is laid layer by layer in a continuous circular pattern on top of a thin layer of aggregate. Each layer is then compacted, forcing the aggregate to expand, thereby tensioning the string loops, which in turn enable the aggregate to jam. The string pattern is computationally designed and robotically fabricated. The first demonstration was built in cooperation with the Self Assembly Lab at MIT for the first Chicago Architecture Biennial in 2015. A small robotic arm mounted on a vertical axis was used to build the structure directly in the exhibition space. The gravel was placed and compacted manually, while the robotic arm laid the string within an incrementally assembled container. By disassembling the container after completion, the non-jammed material fell off and revealed a four-metre tall towering structure, an elevated mass on four slender legs.

Three years later, the Rock Print Pavilion was built in the historical city centre in Winterthur near Zurich, Switzerland. Preceding research into the material properties provided sufficient knowledge to bring the material system into the real world. 30 tonnes of crushed rock and 120 km of string were used to build four curved base walls from which ten columns extended to three metres height. The In situ Fabricator, a robotic arm mounted on a movable platform and developed in collaboration with the Agile & Dextrous Robotics Lab at ETH Zurich, was used to build the pavilion measuring 10 × 8 × 3 m. The robot automatically calculated its position and orientation during the 200 hours of fabrication and was equipped with a custom-built rock print end-effector that allowed the robot to lay continuous string, deposit small batches of gravel and compact both string and gravel. After completion, a crane lowered the roof onto the ten columns adding an additional weight of nine tonnes to further stabilise the structure. During its exhibition, the pavilion was continuously monitored in order to gain insights into the material behaviour. It was both an experiment as well as a public demonstration of the load-bearing capacity and unique architectural potential of Rock Printing. At the end of its lifetime, the structure was reversed to a heap of loose gravel and spools of string.



Gramazio Kohler Research, ETH Zurich

Gramazio Kohler Research, ETH Zurich

Rock Print Pavilion © Aerni

Jammed Architectural Structures © KEYSTONE, Christian Beutler

Rock Print Pavilion © Aerni

Gramazio Kohler Research, ETH Zurich

Gramazio Kohler Research, ETH Zurich

INT: Robotic Building Blocks (2017)
Zoey Tan, Claudia Tanskanen, Qianyi Li, Xiaolin Yin (Design Computation Lab, The Bartlett School of Architecture, UCL)

INT aims to introduce complexity in prefabrication. The team investigates the robotic assembly of bricks, while also addressing the relationship between users and robots. Human interaction is incorporated, through feedback into the robotic assembly process. The design process becomes truly indeterminate and plays out in physical space, allowing for variegating degrees of customisation and order. On the architectural scale, the project establishes a meaningful relationship between degrees of order, fabrication method and human interaction.

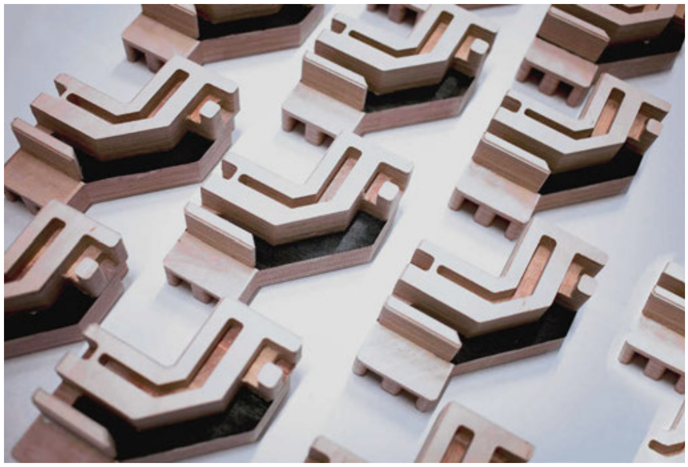
INT addresses a gap in architecture and its production and speculates what role a user can have in the robotic fabrication process. The team has created a digital building block that combines with itself in different ways and can be robotically assembled. These combinations can be written as rules in code in a way that ultimately allows for the creation of an automated design.

These digital blocks are assembled by a robot, which grips them at specifically designed "gripping spots" embedded as part of the block geometry. The blocks are tracked by cameras, informing the robot of the structure it is building and enabling it to react to mistakes. This also opens possibilities for human interaction. When elements are added by a human, the robot can react to them, allowing both human and machine to collaborate in the design process.

The different combinations of blocks are structurally evaluated based on surface area. In parts of a design that require more strength, the ratio of blocks with larger surface area overlaps is much higher. The coding of the block and the surface area calculation that it provides also allow for optimisation of a design.

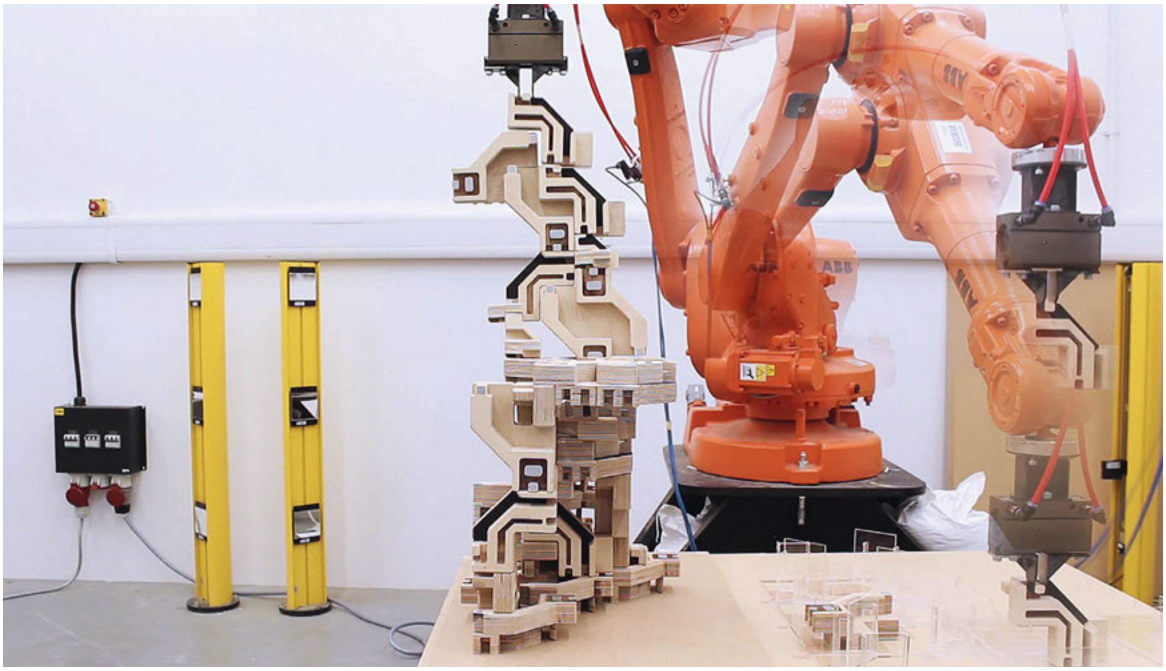
The building system was tested on two chairs that demonstrate the varying degrees of human involvement in the design process. The "mutant chair" is an optimised outcome, emerging only from robotic constraints and algorithmic logic, it has no human design input. This is what the robot understands as a chair. The mutant chair can be constructed in a few minutes, as it uses a minimum number of elements and combinations.

The second chair is a "high-resolution" chair, which was authored by the students by playing around with the design system. The chair has a symmetrical bias and employs a large number of different pattern combinations, resulting in a slightly longer construction time. Furthermore, the team also designed a 2.3-metre-high architectural column consisting of two prefabricated elements.

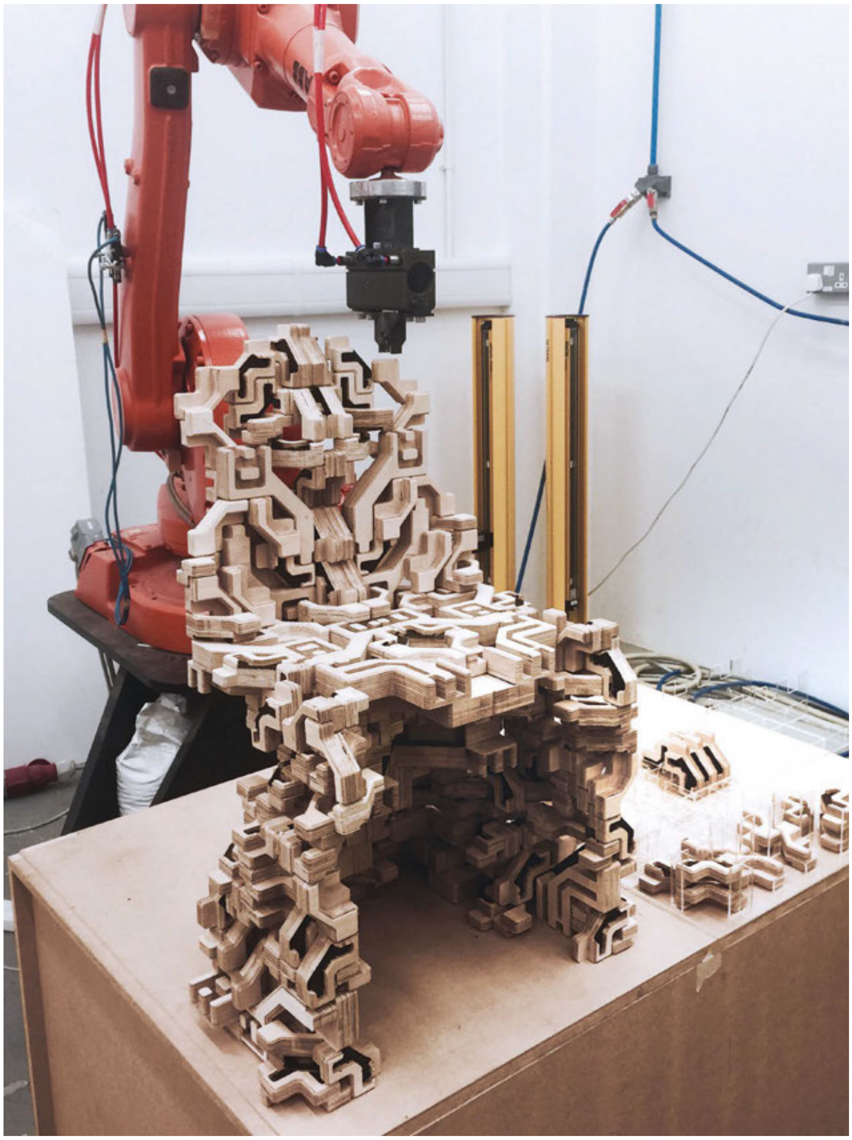


Discrete parts, INT: Robotic Building Blocks, Research Cluster 4, Design Computation Lab, The Bartlett School of Architecture, UCL

Chair model, INT: Robotic Building Blocks, Research Cluster 4, Design Computation Lab, The Bartlett School of Architecture, UCL



Robotic Assembly, INT: Robotic Building Blocks, Research Cluster 4, Design Computation Lab, The Bartlett School of Architecture, UCL



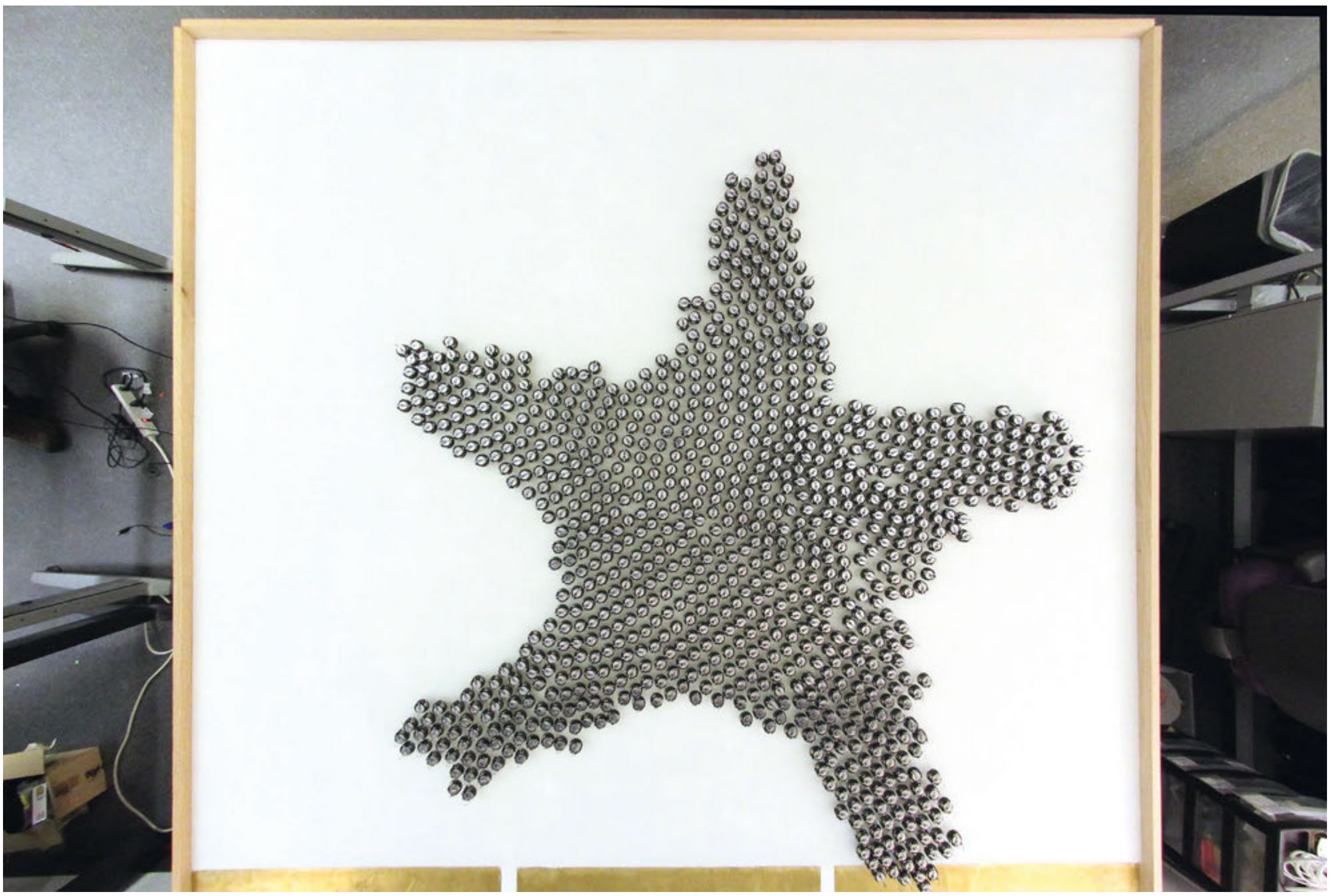
Chair model assembly, INT: Robotic Building Blocks, Research Cluster 4, Design Computation Lab, The Bartlett School of Architecture, UCL

Chapter 4
Many

Chapter 4
Many

This chapter looks at projects that use distributed robots that collaboratively assemble and/or organise material. The robot is distributed among other actors or entities involved in the design and building processes. Distributed robots are not just multiple robots working together on the same process. These robots do not follow a predetermined program. Like swarms found in nature, each robot reacts to its environment in a decentralised way, following a simple set of rules. This type of system deals naturally with uncertainty and other issues that arise when automated processes become more complex. It ceases to be a distinct external force – we will not see the orange industrial robot standing proud. Instead, the robot tends to be integrated into the building element. This approach requires a rethinking of both the building element and the robot that assembles or organises it – these robots are custom designed, just as the parts they operate on. Now, it is no longer only the part that is designed, but also the robot that assembles it. In this chapter, we will see these robots working in collaboration with the material or matter of the construction elements, the environment and other contextual constraints. In contrast to the craft-based approach usually associated with on-site construction, here the factory itself moves to the building site. This chapter competes with the on-site vision for architectural production that Chapter 2: Print presented. It instead proposes a very different scenario, where the question of "site" is not constrained by the specific kind of robot being used – i.e. one with a static base or a robot bigger than the building itself (as with the Khoshnevis or Dini precedents in Chapter 2).

As Matthew Carney has noted in his thesis at the Center for Bits and Atoms at MIT, this kind of robotic assembly "provide[s]



Kilobot, Wyss Institute, 2014

a primary contrast to traditional manufacturing in that the factory is turned inside out: the object being created is itself the framework for the factory." fn. 1 In this chapter, every robot can be understood as a small, moving, distributed local factory, working in collaboration with other mini factories. Like Chapter 3: Assemble, the question posed in this chapter is not about the customisation of material, but the customisation of the assembly. The projects included in this chapter, A Swarm Robot Ecosystem for Autonomous Construction (2017) by Nathan Melenbrink and Justin Werfel (Wyss Institute), Multi-Species Robotic Fabrication for Filament Structures (2015) by Maria Yablonina (ICD Stuttgart) and semblr (2017) by Ivo Tedbury (Design Computation Lab, The Bartlett School of Architecture) each provide possible scenarios for envisioning a fully automated architecture. The worlds they project for us are ones where there are swarms of many distributed, mobile robots assembling materials or assembling building elements in super-customised buildings.

Between Relative Robotics and Programmable Matter

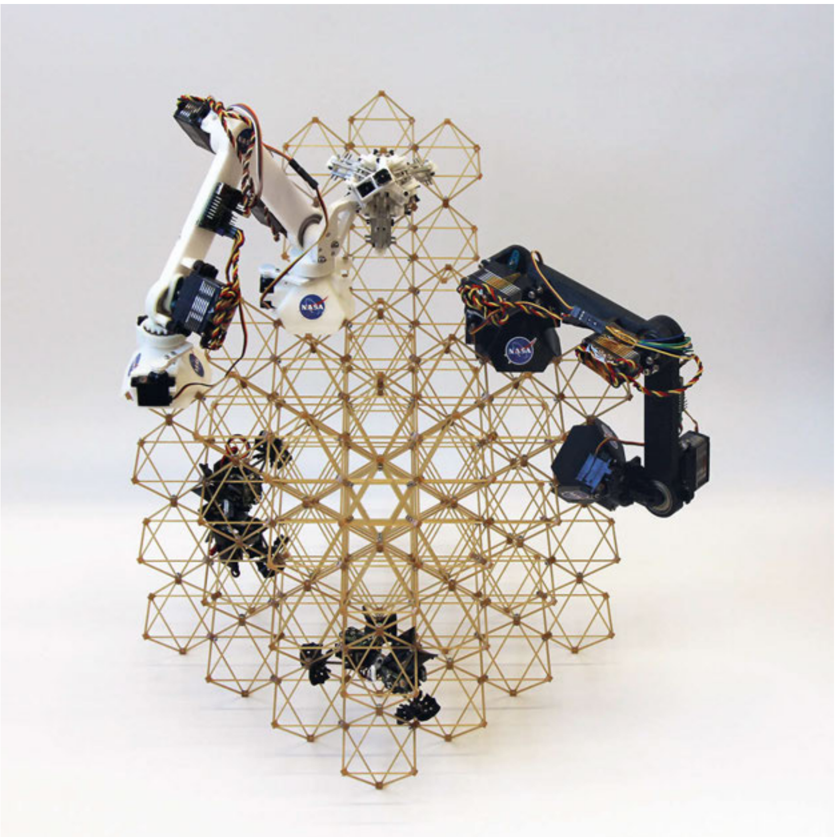
The approach of "many robots" is developed further through a body of research that straddles programmable matter and robotics. As we have seen in discussion in Chapter 3: Assemble, programmable matter is an interdisciplinary research area that looks into matter that can change its physical properties, linking the concept of material with the concept of information. This has been explored widely through the concept of programmable materials. However programmable matter is not necessarily robotic, as the programmable aspect can also be based on material properties (as is the case with meta-materials). Autonomous, modular robots are one approach to programmable matter, where the robots act as "materials" or discrete building blocks, which can reconfigure themselves and establish collective, larger-scale features. Matthew Carney and Benjamin Jenett refer to this type of robot as a "relative robot" – a robot that moves relative to the object it is assembling. fn. 2 Neil Gershenfeld et al. have identified that robotic assembly processes would benefit from an approach using digital materials, pointing out that efforts focusing on the mass customisation of assemblies are in a permanent conflict, as they "seek to decrease the time required by moving more material more quickly, or to increase the complexity that can be achieved by programming motions that cannot be made manually." fn. 3

This approach results in a parallel between data and physical material. A building element becomes a material, with a specific behaviour that is limited and predictable. The behaviour of this material is then considered information and can be programmed to change. Subsequently, computation becomes the reorganisation, recombination or self-assembly of these discrete bits of material or information together. Most emblematic of this approach is the Automatic Modular Assembly System (AMAS) developed by Yuzuru Terada and Satoshi Murata at the Tokyo Institute of Technology. fn. 4 The AMAS robots consist of 4-axis articulated robots. This gives them the minimum degrees of freedom required to traverse the structures they themselves assemble. As with other distributed robot systems, the more interesting part of the research relates to their decentralised control algorithm. There is no centralised system that is aware of where all the modules are located, but the modules can broadcast a signal that has a high value where more modules should be placed and a low value in the area already supplied. Robots can pick up these signals and produce "gradients", with the steepest indicating the probable best place to move towards (or away from). Once it moves one step, the gradients are recalculated and a new best direction is suggested. This borrows from continuous optimisation techniques used in mathematics, such as gradient descent.

Another important precedent for an approach utilising many modular robots is the Structure-Reconfiguring Robots developed by Franz Nigl, Shuguang Li, Jeremy E. Blum and Hod Lipson. The prototype Robot R2 they developed is a climbing robot capable of reassembling a standard timber strut into a variety of structures. fn. 5 In both the AMAS example and Robot R2 example, the structural module and the assembler robot have different geometries, and the assembler robots are active while the structural modules are passive. The scenario in these two examples is one where there are many generic, universal building blocks which are reconfigured by many active more-specific robots.

The Center for Bits and Atoms at MIT has used this approach mainly for work in mechanical engineering alongside NASA in situations where repair or modification of structures is highly difficult, such as in aerospace. fn. 6 Robots such as the BILL-E robot Kenneth Cheung and Benjamin Jenett designed to assemble space-frame satellites in outer space. BILL-E is based on flexural material, a type of digital material that has extremely strong mechanical properties, making it suitable for aerospace. The material properties are "meta", i.e. coming from the geometric organisation of the elements rather than the physical material properties itself – one of the key characteristics of digital materials. fn. 7

In our work in Design Computation Lab, we have been asking the question driven by this difference: what if discrete building blocks of architecture and the robot that assembles them have the same geometry? In PizzaBot: Assemble/r Assemble (2018) developed with students Man Nguyen, Mengyu Huang, Martha Masli, Wenji Wang and Dafni Katrakalidi, a relative robot takes the shape of a simple box and is made out of a common and readily available sheet building material. Using a single revolute joint, the pizza box-shaped robot



Bill E Robot, Center For Bits and Atoms, MIT, 2017

PizzaBot, Design Computation Lab, The Bartlett School of Architecture, UCL, 2018 can change direction, picking up a passive building element that has identical geometry. The geometry enables efficient communication between both elements. The many PizzaBots can use already-assembled building elements as paths in order to climb the structure and continually assemble. In addition, one PizzaBot can combine with another into a more complex, multi-axis robot that is capable of solving more difficult assembly problems. As they are distributed, the question of on-site or off-site is no longer an issue, as distributed and relative robots are neither one nor the other. The robots use the material or matter they deposit as the "site" and therefore it is continually changing, adapting and evolving according to the distribution and redistribution of building elements. The deposited matter provides the factory precision gained in other robotic approaches.

When combined with logic of swarm intelligence – according to Eric Bonabeau et al., i.e. "any attempt to design algorithms or distributed problem-solving devices inspired by […] collective behaviour" fn. 8 – and cellular automata, this new kind of digital assembly moves outside the factory, to the building site. Historically, the building site was associated with artisans, craftsmen, imprecision and improvisation. Instead, the building site now becomes the place for the organisation of data. This kind of system is most effectively controlled in a distributed way – every particle of block makes its own decisions in response to the group. This characteristic is emblematic of swarm intelligence, where global order emerges from lower level actions.

Modular Robotic Autonomy

Modular robots have to be much more autonomous than standard, static industrial robots. They need to be able to make decisions autonomously, to react to themselves and to their environment. The notion of an AI is linked to these kinds of robots, as they need to have their own intelligence in order to complete tasks. Rather than preprogramming the design and then having it executed, the design can emerge from the interaction of modular autonomous robots. The Wyss Institute at Harvard University has experimented with this, for example with the Kilobot and Programmable Robot Swarms project (2014), which has 1000 robots collaboratively constructing larger wholes. fn. 9 As we saw in Chapter 3: Assemble, the idea of the autonomous machine goes back to work of cyberneticists and architects of the 1940s–1970s such as the work of Nicholas Negroponte. In one way, this could be seen as the update of Negroponte's SEEK (1970), where, in this version, among the gerbils there would be an autonomous gerbil rearranging blocks of matter (instead of a robotic arm).

Perhaps the moment AI and architecture come together is in this form of many robots. AI has been used before to generate designs, but this does not break the traditional gap between "digital design" and "digital fabrication", or in terms of representation. Developing an autonomous constructor would be a sort of logical end-point of a fully automated scenario. There would be no preprogrammed design. Instead, there would be a swarm of robots collectively constructing an organisation of parts into a building that corresponds to certain requirements or goals. This disrupts all classical notions of design, authorship and time. It is important to note that there are some steps being made towards this: autonomous construction machines also already exist, such as autonomous excavators (such as driverless cars). In the context of climate change, these are useful to reorganise and shape terrains.

Here there is a difference between modular robots that operate on a modular material (AMAS, TERMES, BILL-E) and modular robots where the robot is the material (Hod Lipson's Molecube (2005) or Kilobot). In architecture, it seems logical that not all the material assembled is robotic and remains robotic. The Fun Palace (Cedric Price, 1959–61) idea of interactivity would suggest a completely interactive building where all parts can continuously change and adapt positions. However, this seems an almost mystical future and would require that the robots used would be extremely cheap for the project to be viable. The projects in this chapter do not propose that scenario.

It has already been hinted at in Chapter 2: Print that printing a disruptive, radical solution to the assembly problem would get rid of the notion of the part. Of course, in the case of 3D printing, this does not work because matter is continuous and cannot be edited. The domain of programmable materials and autonomous robotics allows this kind of ultimate scenario of universal construction. It is a form of assembly that is fundamentally new: generic, universal building blocks that are programmed or can be programmed to construct larger-scale forms and features. There are no more external robots as in Chapter 3: Assemble. Compared to Chapter 2: Print, the programmable matter in the many robots approach could have different material features such as insulation, electrical conductivity etc. The assemblies in this chapter can therefore be functional and multi-material.

Towards Modular Robotic Assembly

The approach presented in this chapter is dialectically opposed to the traditional notions of mass customisation of building elements that have been favoured by architects since the first digital turn. The approach of using "many robots" argues that it is not the parts that should be customised, but their assembly or organisation. This is a very similar argument to the one presented in the previous chapter through the assembly problem. In the case of many robots, one type of robot (or a limited number of robots) needs to be able to deal with all the building blocks. In this chapter, we look at two different types: specialist distributed robots and modular distributed robots (as briefly presented above). Specialist distributed robots are robots that do not work with modular or discrete materials. Instead, projects that use distributed robots, such as Minibuilders (2014) developed at the Institute for Advanced Architecture of Catalonia, tend to make use of a continuous material – extruded concrete – rather

Kilobots, Wyss Institute, 2014

than a modular one. In Minibuilders, researchers developed a family of three construction robots, each with a different role: Base Robot, Grip Robot and Vacuum Robot. fn. 10 The robots navigate over the material they have already deposited. In a sense, they are distributed 3D printers – taking what would have happened on a gantry in Chapter 2: Print and distributing it. In the case of Minibuilders, the material cannot be edited and is meant for a final state only. This approach is different from those that use modular robotics and programmable matter, as the latter allows continuous modification and adaptation. There is no final state of construction when using modular robots.

Modularity and the Welfare State

Historically, modularity has proved to be an interesting issue for architects and a useful political tool for governments. Whereas the 1990s and early 2000s' mass customisation approach argued for complete differentiation of building elements, basing itself on a paradigm of digital craft, this approach advances older modernist and industrial tropes of modularity, universality and seriality. When looking back in history, one need not look far to see this approach as key to many of the most canonical architects of the 20th century. Post-World War II reconstruction needed to house hundreds of thousands of displaced people throughout Europe. In order to avoid the slums resultant of earlier 19th century approaches to building, a complete overhaul of building technology was required. Nicholas Bullock and many other scholars have written extensive studies of this period, and therefore this text is not really the place to elucidate much further on the topic, other than noting the following: what was key to the reconstruction of Europe was the social agenda it was tied to. Whatever approach was developed, it had to be able to establish a "new world order" just as much as it had to provide a sense of continuity and community. fn. 11 Reconstruction in Great Britain, signified by the 1942 Beveridge Report, was tied explicitly to the development of a welfare state. fn. 12 Welfare states are successful when they are able to be universally adaptable to differences between people, contexts and environments. They fail when a one-size-fits-all model is applied. fn. 13

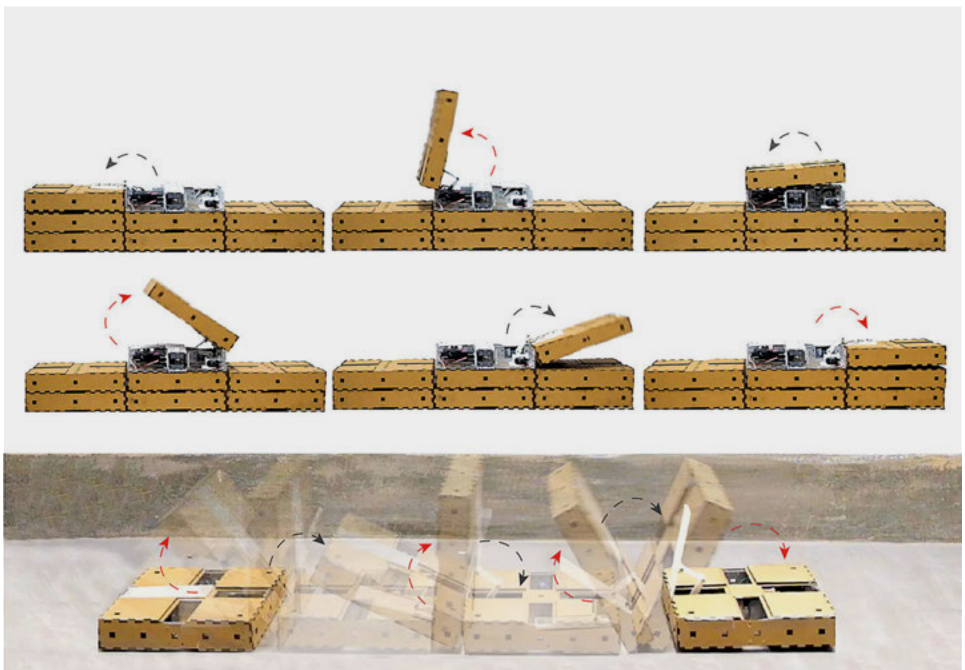
While critique of much of the post-war reconstruction effort in the UK has resulted in the demolition of the efforts of mid-20th century architects, from Robin Hood Gardens (c. 1972) by Alison and Peter Smithson to the Southgate Estate (c. 1977) by James Stirling, the project of reconstruction invented a new industrial production chain for off-site prefabricated concrete elements, which was used to quickly assemble housing across Europe. From Le Corbusier's Maison Dom-Ino (1914) to Jean Prouve's Maison Tropicale (1949–1952) to efforts in the Soviet Union to organise industrial production, the universal standardised

Autonomous Walking Excavator, Robotic Systems Lab of Prof. Marco Hutter, ETH Zurich, 2018 housing produced in this period can be seen as a precedent for automated assembly. All were systems of construction that relied on underlying rule-based thinking. Without any doubt, these efforts often resulted in homogenous and repetitive architecture. But as we will see in the projects of this chapter, today we have the possibility to utilise modular robotic assembly to organise architecture that has a high degree of customisation, despite being manufactured out of repeating, generic, universal elements. Modernist efforts to pull together industry and architecture post-World War II were in response to an extreme need for housing plus a growing political conflict between East and West, where the western welfare state had to prove that it could compete with the Soviet Union in terms of housing construction and universal access to housing. fn. 14 Today, we are rapidly heading towards a similar but even more unprecedented situation that could form an incentive to radically change building construction: the global housing crisis with the urgent need for new homes, combined with a global climate crisis which will require changes to our coastlines on a territorial scale. This scenario could form an incentive as strong as post-war reconstruction that could push us to fully develop automated construction.

There is an important notion of labour that is associated with this approach. As mentioned previously, in the 1990s and early 2000s, architects mass-customised and differentiated building elements, while rarely considering the amount of labour that this would generate in the assembly process. Automation was considered only within the design-as-virtual space, but never moved to the actual building site. The projects and precedents explored in this chapter shift this approach to labour, proposing a workflow that is fully automated or, at minimum, is aware of the amount of labour required for assembly.

Disruption Beyond the Discipline

While in this chapter we are clearly positioning the "many robots" approach towards a scenario in which there is full automation, it also requires a disruption of the design and building industry. Previous chapters mainly made use of a universal robotic arm, which acts as a platform for many different actions. Architects were also often using existing materials. The specialist distributed robot approach is a task-specific robot, which is not universal. Instead, it is unique to whatever it assembles. Maria Yablonina's Multi-species Robotic Fabrication for Filament Structures (2015) project proposes to decentralise the robot, but the robot makes use of a continuous material filament that can be spun into a variety of structures. In this case, we are looking at a system that is highly specific and material dependent, but one which also



Pizzabot, Design Computation Lab, The Bartlett School of Architecture, UCL, 2018 manages to distribute the construction. This kind of approach is best suited for very specific scenarios such as large-scale in-situ spanning structures that are generally not changeable.

In the case of many modular robots, both robot and material need to be invented from scratch. For every new kind of building element, a new robot has to be developed and vice versa. This approach therefore economically requires the widest possible application to be able to offset the cost of its development. This means that building elements and robots should logically be as generic as possible and can be developed only for applications that are either generic – as in the adoption of Le Corbusier's Maison Dom-Ino system in post-World War II reconstruction – or on extremely large scales in increasingly common scenarios affected by issues such as climate change.

For example, scenarios where modular robotic assembly could be applied include the case of hazardous, high-risk or dangerous environments such as post-disaster scenarios or remote territories that are difficult to access, from mountainous areas to extra-terrestrial environments. [fn. 15] A Swarm Robot Ecosystem for Autonomous Construction (2017) by Nathan Melenbrink and Justin Werfel (Wyss Institute) proposes the use of modular robots on a territorial or geographical scale in order to reinforce existing coastlines and build dykes to prevent coastal erosion or a family of robots to reinforce ecosystems threatened by climate change. Additionally, in the context of rising pressures on housing worldwide, mass-housing could be a possible application for Melenbrink and Werfel's distributed robots, too. Melenbrink and Werfel's TERMES robot, presented in this chapter, is a small robot that is able to pick up a custom-designed building block that also forms a guideline and ground for the robot to walk over.

However, as we have seen in the introduction, the issue is not only technological – it also has important political implications. Although there is economic and societal pressure that would allow a fully automated system for architectural production with distributed modular robots to exist, the question remains: what would the consequences of this scenario be? How closed or open is this system? If every custom-designed building block or building system requires its own distributed robot, then what does that mean for design? Would everything then be based on just a single module or generic voxel, depending on the most prevalent and affordable distributed robot? This is a scary scenario but seems like a logical consequence of shifting the question from highly customised building elements to customised building assemblies.

In his project semblr (2017), Ivo Tedbury (Unit 19, Design Computation Lab, The Bartlett School of Architecture, UCL) suggests a scenario where a government or very large cooperative invests in developing the robotic technology for fully automated housing. The robots become part of the service of the government body, with citizens having the right of access to these robots to construct their housing. This scenario is similar to the postwar effort of both western and Soviet governments to invest in publicly funded housing construction – however, it holds the possibility for small-scale customisation. On the other hand, a large private company could raise the investment to set up a fully automated housing platform. This would result in very different consequences, with potentially one single company able to both absorb the entire market of building products, building construction, building design and development, and able to capitalise on thousands of rent-paying citizens. The fact that the robot and the building product are linked together and the technical difficulty of the concept, generates a system that is prone to monopolisation. The amount of capital necessary to establish this system makes it less accessible for small user groups or open-source approaches. Perhaps the approach of Year Zero or the housing crisis would be strong enough incentives for investment in this model by more democratic bodies of governance or management. However, it remains a large and open question as to how utopian this scenario is. Architecture may just require a slightly dumber, less radical solution than swarms of construction robots. Just as the Maison Dom-Ino, it is a model that is almost too obvious and simple that becomes replicable over the whole world. Swarm robots may not be that exactly.

While the many robots approach mainly references innovations from mechanical engineering, it is important to point out the architectural consequences of these systems too. The approaches developed in this chapter and Chapter 3: Assemble start to redefine architectural syntax. We are not working with modernist types any more – where elements perform singular functions such as columns, beams, bricks, floor slabs etc. Instead, we are looking now at an architecture of a radical simplicity, where parts are limited and not restricted to a single function: they can be polyvalent. In this, production chains are simplified. Instead of thousands of parts having to come together, we now have only a few. With or without robots, a change in syntax, tectonics and production is an already significant shift in the way we produce the built environment.

fn. 1 Matthew Carney, Discrete Cellular Lattice Assembly, Massachusetts Institute of Technology, Master's dissertation, 2015, 17, accessed: http://cba.mit.edu/docs/theses/15.09.Carney.pdf.

fn. 2 Carney M, Jenett B. Relative Robots: Scaling Automated Assembly of Discrete Cellular Lattices. ASME. *International Manufacturing Science and Engineering Conference,* Volume 2: Materials; Biomanufacturing; Properties, Applications and Systems; Sustainable Manufacturing, 2016.

fn. 3 Neil Gershenfeld, Matthew Carney, Benjamin Jenett, Sam Calisch and Spencer Wilson, "Macrofabrication with Digital Materials: Robotic Assembly", *Architectural Design*, Volume 85, Issue 5, Special Issue: Material Synthesis: Fusing the Physical and the Computational, September/October 2015, 123.

fn. 4 Yuzuru Terada and Satoshi Murata, "Automatic Modular Assembly System and its Distributed Control", *The International Journal of Robotics Research,* Volume 27, Issue 3-4, 2008, 450, accessed: https://journals.sagepub.com/doi/pdf/10.1177/0278364907085562.

fn. 5 Nigl, Franz & Li, Shuguang & E. Blum, Jeremy & Lipson, Hod. (2013). Structure-Reconfiguring Robots: Autonomous Truss Reconfiguration and Manipulation. *Robotics & Automation Magazine,* IEEE. 20, 60-71.

fn. 6 Greenfield Trinh, et al, "Robotically Assembled Aerospace Structures: Digital Material Assembly using a Gantry-Type Assembler", *bler, 2017 IEEE Aerospace Conference proceedings,* March 2017, accessed: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170006474.pdf

fn. 7 Benjamin Jenett and Kenneth Cheung, "BILL-E: Robotic Platform for Locomotion and Manipulation of Lightweight Space Structures", 25th AIAA/AHS Adaptive Structures Conference, January 2017, accessed: https://arc.aiaa.org/doi/10.2514/6.2017-1876.

fn. 8 Eric Bonabeau, et al, *Swarm Intelligence: From Natural to Artificial Systems,* Oxford University Press, 1999, 7.

fn. 9 Michael Rubenstein, Alejandro Cornejo, Radhika Nagpal, "Programmable self-assembly in a thousand-robot swarm", *Science,* Volume 345, Issue 6198, 15 Aug 2014, 795-799, accessed" http://science.sciencemag.org/content/345/6198/795.

fn. 10 https://iaac.net/project/minibuilders/

fn. 11 Nicholas Bullock, *Building the Post-war World: Modern Architecture and Reconstruction in Britain,* Routledge, 2002, 7.

fn. 12 Sir William Beveridge, "The Beveridge Report", Presented to Parliament by Command of His Majesty, November 1942, accessed: https://www.sochealth.co.uk/national-health-service/public-health-and-wellbeing/beveridge-report/.

fn. 13 Referring here to the current UK government's roll-out of Universal Credit, which has been widely criticised in the press and elsewhere as being the "biggest public policy failure" since the late 1980s/early 1990s. https://www.independent.co.uk/voices/editorials/universal-credit-government-failure-national-audit-office-report-alok-sharma-a8400961.html

fn. 14 Reinier de Graaf, *Four Walls and a Roof: The Complex Nature of a Simple Profession,* Harvard University Press, 2017.

fn. 15 Some of the most recent provocative work utilising mobile modular robots to speculate on these very scenarios have come out of Design Research Lab at the AA School of Architecture, where the majority of the authors of this book either studied or taught.

Semblr, 2017

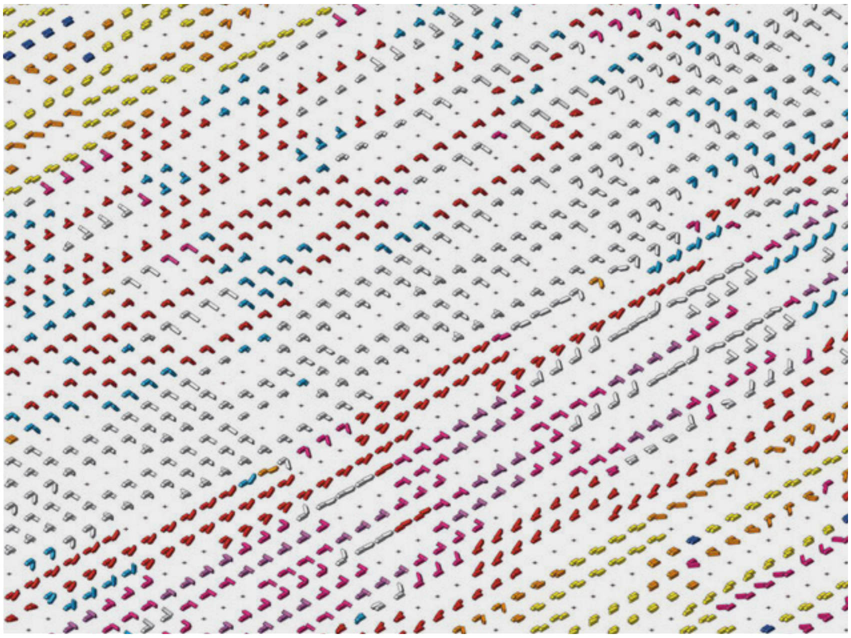
Ivo Tedbury, Unit 19, Design Computation Lab, The Bartlett School of Architecture, UCL

semblr is a platform for automated construction. It uses discrete timber bricks and distributed robots that move relative to the structures they assemble, allowing data-driven autonomy of both design generation and construction through one integrated syntax. A relative robot system has the key advantage of circumventing external infrastructure constraints to allow unlimited form and size. For the *semblr* system, reversibly connected aggregations of hollow, composite timber "bricks" are both the desired construction objective and the assembler robots' locomotion infrastructure.

The timber brick aggregations are "digital materials", which are "assembled from a discrete set of parts, reversibly joined in a discrete set of relative positions and orientations" fn. 1 adjacent to one another. Bricks can be arranged by selecting a connection point on one brick and orienting another brick around another selected connection point. Thus, aggregations can be expressed as compact numerical data, bypassing the need for conventional 3D modelling and production of construction information. The key to this approach is immediacy from design to construction environments: they both use the same syntax.

The brick connection points form a digitally and physically structured environment over which the robots can navigate and climb. This removes the need for additional orientation systems for the robot, as locational error is mitigated to the nearest discrete connection point step. Three end-effectors are used: two are dedicated to the robot's bipedal movement, and one carries and positions the brick. Due to the reversible connection system, intermediate states can be included in the construction process. This "whole-build" approach removes the need for extraneous equipment such as cranes, scaffolding and formwork.

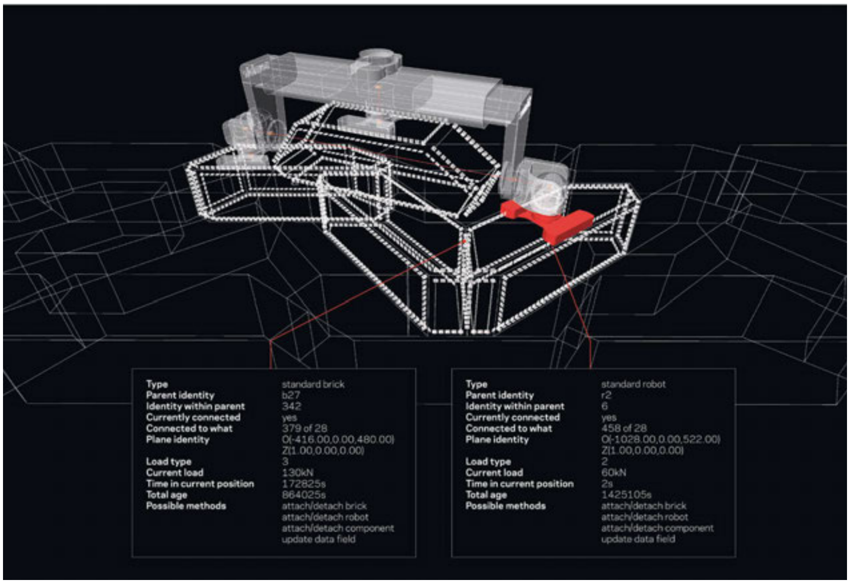
Overall, the project suggests a sustainable material system, designed using data-driven generative algorithms and robotically assembled. This radical proposition challenges the role of robots in the economy as objects of capital. Taking inspiration from the Accelerationist political movement, the project occupies a transition between current "accepted" processes of capitalism and the "desired" processes of an automated post-capitalist future.



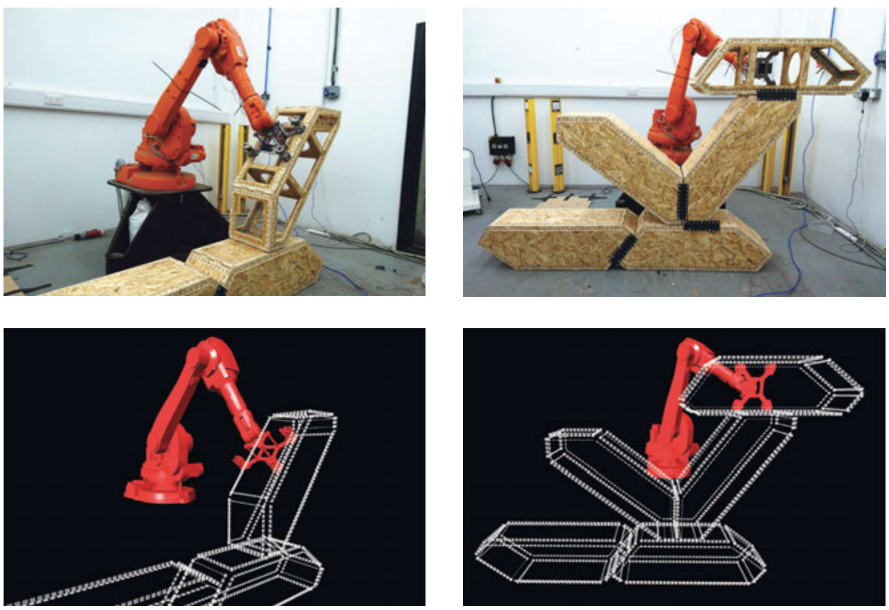
Generated combinations, semblr, Ivo Tedbury, Unit 19, Design Computation Lab, The Bartlett School of Architecture, UCL, 2017

fn. 1 Gershenfeld, N. et al. (2015). Macrofabrication with Digital Materials: Robotic Assembly. *Architectural Design,* 85(5), pp. 122-127.

Small Dwelling Exterior, semblr, Ivo Tedbury, Unit 19, Design Computation Lab, The Bartlett School of Architecture, UCL, 2017



Data connections combined, semblr, Ivo Tedbury, Unit 19, Design Computation Lab, The Bartlett School of Architecture, UCL, 2017



Robot Assembly Test, semblr, Ivo Tedbury, Unit 19, Design Computation Lab, The Bartlett School of Architecture, UCL, 2017

Multi-species Robotic Fabrication for Filament Structures: Towards a Robotic Ecosystem, 2015

Maria Yablonina, Achim Menges

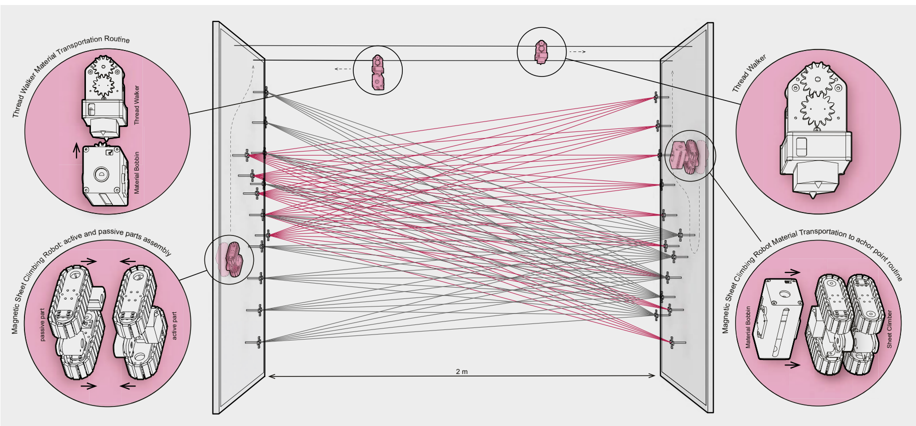
Industrial robotic tools appropriated for architectural fabrication in the past decades have played a pivotal role in materialising computational design concepts, bridging the gap between speculation and physical form. However, machine-like robot arms introduce severe scale limitations, inherited from the assembly line logic for which they were originally designed. The fundamental distinction between manufacturing and construction processes, expressed in the physical relationship between the product and the manipulator, implies a significant rethinking of automation logic towards a system where the product, i.e. the building, is stationary and the robots must change their location. fn. 1

This research aims to expand the design space of architectural form and materiality through augmenting or replacing industrial off-the-shelf machines with an ecosystem of task-specific robots. Our current catalogue of robot species and complementing design and control software was developed for tensile filament structures. Low-cost, agile and comparatively effortless-to-deploy mobile machines can leverage the properties of lightweight filament materials towards large span structures built in situ.

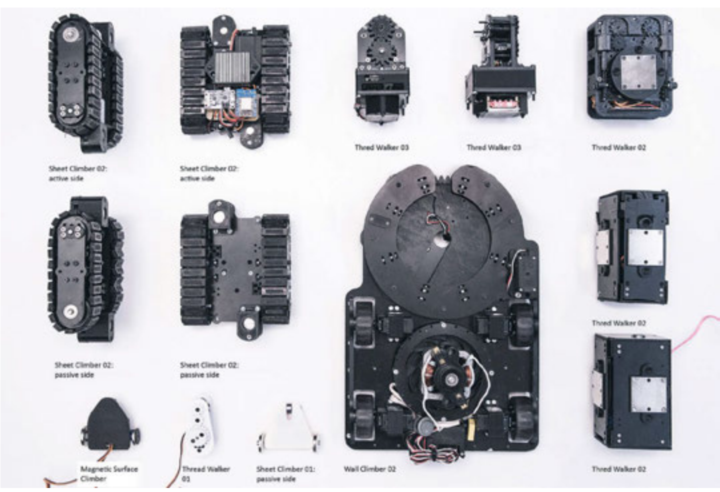
Currently the catalogue includes three species. Each robot incorporates a unique locomotion strategy, a sensing system, a control method and a set of actuators for material manipulation or collaboration tasks. Material manipulators attach the filament to preinstalled anchoring details and transport the material cartridges between the machines. All robots within the system are capable of communicating with each other and the operator via a central server.

Three objects were produced to test the system's on-site deployability, scalability and increase in efficiency as more machines are added to the system. The outcome of two of these experiments were exhibited in public spaces accompanied by live machine demonstrations. The proposed system establishes the possibility of creating hierarchical multi-species robotic systems capable of navigating construction site environments and performing fabrication tasks cooperatively. Such systems imply a significant rethinking of the design and planning strategies for architectural artefacts.

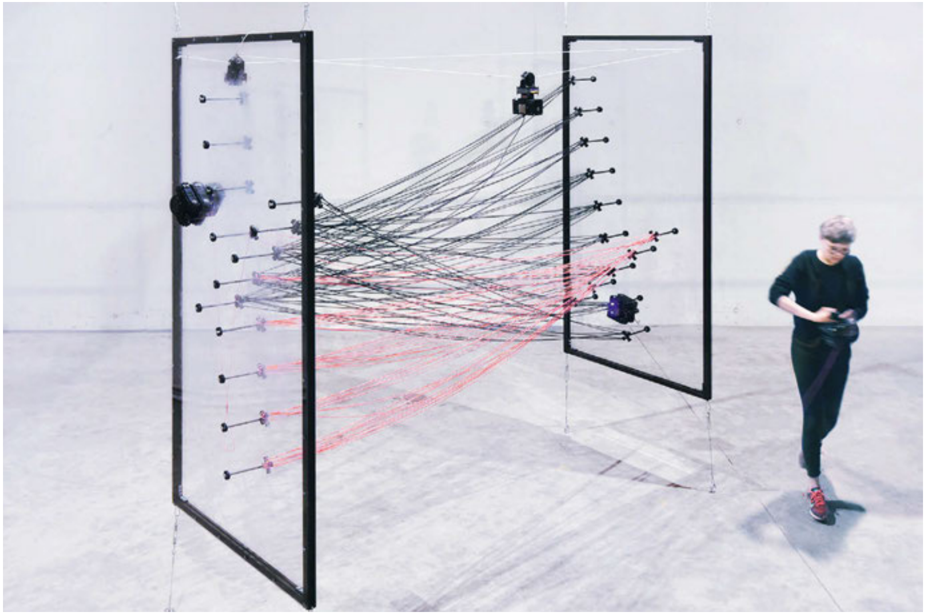
fn. 1 Cousineau, L., Miura, N.: Construction Robots: The Search for New Building Technology in Japan. American Society of Civil Engineers (ASCE), Reston, VA (1998).



Demonstrator, fabrication process diagram © Maria Yablonina, ICD, University of Stuttgart



The Catalogue of Filament-Specific Mobile Robotic Species. © Maria Yablonina, ICD, University of Stuttgart



Demonstrator Result 3 © Maria Yablonina, ICD, University of Stuttgart

Demonstrator 01 Outcome © Maria Yablonina, ICD, University of Stuttgart

Demonstrator 02 Result © Maria Yablonina, ICD, University of Stuttgart

A Swarm Robot Ecosystem for Autonomous Construction, 2017
Nathan Melenbrink & Justin Werfel

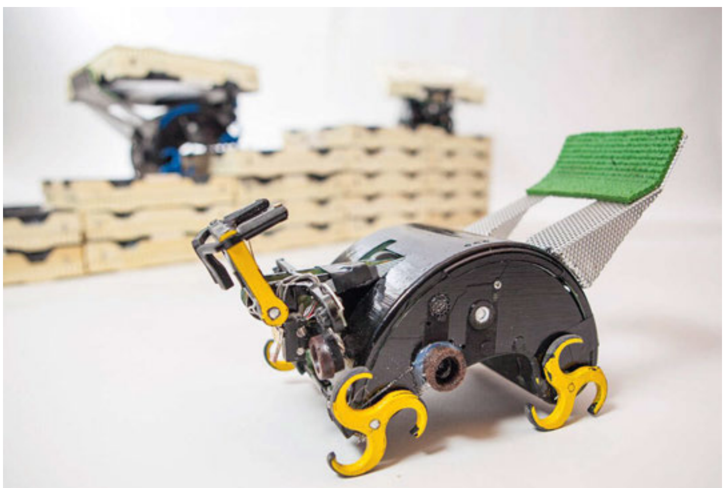
While the predominant mode of automation in the construction industry has been off-site prefabrication, this can ultimately account for only a certain subset of construction tasks. Despite its challenges, on-site automation will be necessary in order to enable fully autonomous construction.

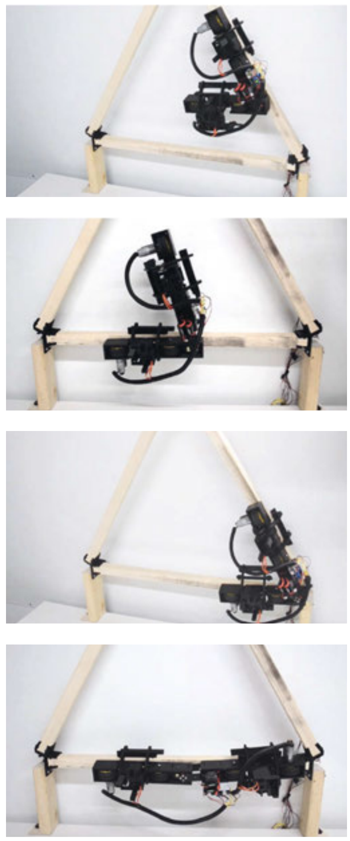
One path for automating construction is to draw inspiration from nature's collective builders, animals such as termites, beavers and weaver birds, whose resilient building techniques are ideal for application scenarios without human supervision. These animals build structures much larger than themselves, making faster progress than single agents could through the parallelism of the swarm. They coordinate in real-time by responding to local stimuli, as opposed to the detailed phasing and preplanning ubiquitous in commercial construction. Their natural construction processes are thereby more robust in response to individual failures and mistakes, variation in the size of the collective or changing site conditions than typical human methods. This principle is one we can harness for swarms of construction robots.

The project provided a physical demonstration as well as an algorithmic framework for a decentralised team of robots collectively building structures larger than themselves. The robots are fully autonomous, use only local information obtained from on-board sensors and coordinate through shared manipulation of the structure they build, inspecting local geometric configurations of material they encounter as they go. The structures built by the robots require a flat foundation and are unable to cantilever or span over unsupported distances. Such limitations could be addressed by introducing other collectives of robots to the ecosystem, for example one that assembles truss elements.

Building structures that are not fully supported introduces new possible failure modes that the robots need to be able to prevent continuously throughout construction. One possible approach for an autonomous truss assembly system uses internal forces within the structure as the stigmergic cue that robots use for coordination. In the simulation, we developed theory for how distributed climbing robots can use local force measurements to both monitor structural state and guide building activity.

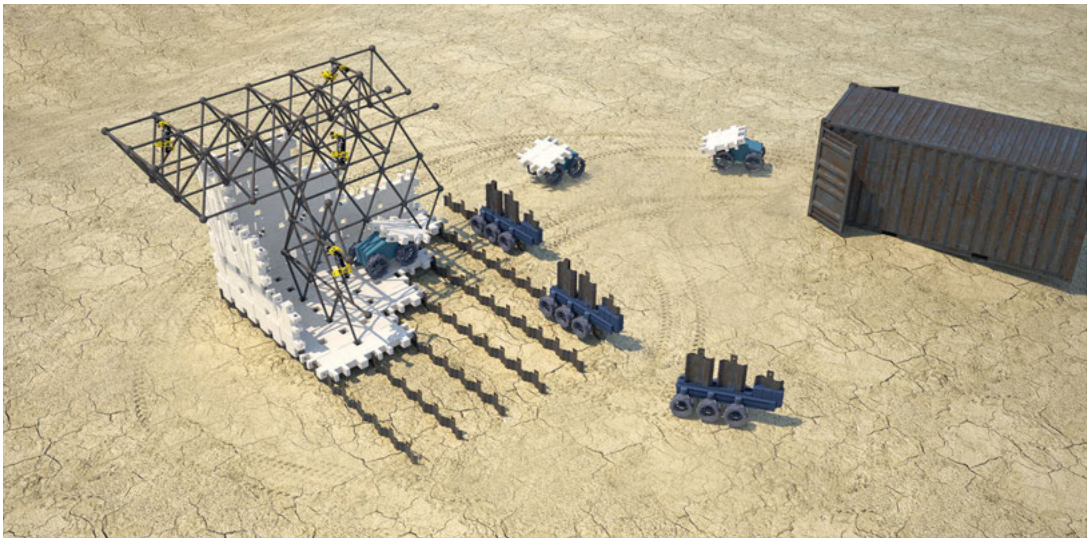
TERMES robots are fully autonomous, using only local information obtained from on-board sensors. Image © Eliza Grinnell, Harvard School of Engineering and Applied Sciences





The locomotion sequence as the robot transitions from one strut to another © Nathan Melenbrink

A hypothetical distributed team of climbing robots collectively build a cantilevering truss © Nathan Melenbrink



Ecosystem of 3 robot swarms working in concert on a hypothetical construction project © Nathan Melenbrink

The swarm approach is well-suited to large-scale, environmental restoration construction tasks, such as mitigating coastal erosion or desertification © Nathan Melenbrink

Chapter 5
Diffuse

Chapter 5
Diffuse

The ephemeralisation of robots and automated systems is by no means new, as throughout history – particularly in the 19th and 20th centuries – robotic machines were presented widely in literature, from Mary Shelley's *Frankenstein* (1823) to Marge Piercy's feminist classic *Woman on the Edge of Time* (1976) and in cinema from *Blade Runner* (1982) to *The Stepford Wives* (1975), *The Mechanical Man* (1921) and *Metropolis* (1927) serving as narrative underpinnings for the projection of both techno-positive and techno-phobic futures. Primarily, their inclusion in story-telling served, as the historian Antoine Picon has noted, as important mechanisms "to suggest, without unnecessary heaviness, that they [robots] could lead to widespread change". fn. 1 Picon further suggests that the narrative of the industrialisation of construction (or for our purposes, the history of robotic building) can be assimilated into the development of what he refers to as "utopian" social and economic concerns, such as personal mobility, personal freedom, the right to safety, quality places to live in and the right to leisure. fn. 2 It is this connection between labour, value, economy and robots that gives us a proving ground for speculating on the consequences of what exists today: the complete diffusion of robotic technologies into everyday life; from the domestic realm with personalised environmental control to the ways we navigate our cities and the means through which rural communities access much-needed services. The projects included in this chapter, M. Casey Rehm of Studio Kinch's HoaxUrbanism (2017) to Jose Sanchez's Common'hood (2019) to Greg Lynn's RV Prototype House (2012), all demonstrate ways that we can interpret and inhabit our environments via the expansion of automated robotic technologies into our everyday lives: economically, socially, politically and environmentally. We are in a period of what was once science fiction now coming to life.

This leads us to divert from the path set in each of the previous chapters: here, we will see very little of the "generic", orange, industrial machine. Nor will we see projects which are necessarily physical in their realisation. Instead, the projects speculate on further avenues for questioning what a robot in architecture is, what automation in architecture means and what value it holds for the future. This chapter is interested in looking at the possibilities provided by and consequences of moving towards full automation of the built environment. In particular, we are concerned with how the complete diffusion of robotics and automation into everyday life will enable society to move towards one which is more equitable and democratic: towards a society that allows for more leisure and less need to earn money just to (barely) survive. In our own work, we aim to always be explicit about how robotic building and automation can be transformative for our social practices, not only as architects and builders but also as inhabitants of the world in the 21st century.

Architectural Accelerationism

The shift towards full automation in architectural design and construction is an inevitability. This in itself is not at all a new idea: the 20th century economist John Maynard Keynes predicted as much in 1928 when he coined the term "technological unemployment" to describe what would occur when automated technologies were used to replace many jobs that required manual labour. fn. 3 And it is also not new within the discipline of architecture itself – as philosopher Adam Greenfield has recently written, post-work societies have been explored throughout the 20th century, from Situationist International to Constant Nieuwenhuys's lifetime work New Babylon and the Italian collectives Superstudio and Archizoom. However, these examples were framed mainly around more esoteric notions of "self-actualisation and play", fn. 4 rather than the economic and social consequences of a world without (or with less) work that are pertinent to our present concerns.

If we are to look towards the fringes of cultural and architectural theory today, we can find a group of thinkers investigating the consequences of a post-work world because of human technological advancement. This includes left techno-accelerationists Nick Scrnicek, Alex Williams, members of the feminist collective Laboria Cuboniks, members of the Autonomy Institute and theorists, economists and sociologists such as Greenfield, Benjamin Bratton, Luciana Parisi, Aaron Bastani and Erik Brynjolfsson and Andrew McAfee. All of these thinkers share the concern that the way in which we embed technology into our everyday lives – and the consequences that this holds – is (or should be) a main concern of designers today.

But if we look more towards the centre (as if we can define a centre) of disciplinary matters, work that approaches full automation as the key concern of architecture in the 21st century is few and far between. As architecture historian Mario Carpo has acknowledged, while the architects of the first digital turn of the early 1990s "embraced digital change sooner than any other trade, industry, or creative profession", fn. 6 architecture and construction are far behind other industries in embracing the potential of automation to enact widespread change. And this is not just in the way we utilise fabrication and assembly processes (design being one area where algorithmic automation is now more commonplace) as we have seen elsewhere in this text, but also relates to how architecture's relationship(s) to automation reflects the way in which we want to communicate and disseminate work, and how the framework for our relationship to technology projects an alternative future(s). Any denial of the role that robotic technologies will play in the future is a dangerous game; we risk making architecture seem technologically out of touch as other fields continue to march on ahead in their adoption and integration of automation, and the discipline leans towards looking inwards instead of outwards.

The Age of Intelligence

Cyberneticist Norbert Wiener pointed out over six decades ago that the state of contemporaneity is able to be understood only through the way in which communication occurs: how messages (data) are exchanged and thus the technology used to do this exchange. fn. 6 It is pertinent to think of someone such as Wiener, considered to be the father of cybernetics, because his model for enabling progress and preventing entropy – via systems of feedback between man, machine and environment – helped form the foundations of how automated systems have been deployed today. As the projects will show, we are far beyond the "blind, deft and dumb" machines used by Gottfried Leibniz in the 17th century – instead, we are in an age of intelligence, fn. 7 where robotic systems are distributed across platforms and scales. It is useful to adopt the approach of Bruno Latour here in his work on scientific production, where we can view our work as architects not as the product of the single-minded "Master" architect but the outcome of the many ways in which we engage with social, political and technological practices.

The automated systems embedded in our everyday life (machine learning, the Internet of Things, big data) allow us to engage with our environment with a degree of precision and detail of information about that environment that was never possible before.

What is perhaps important to add to this conversation is that we also need to ensure that we can critically understand the ways that those systems are contributing continuously to the ongoing organisation and shaping of the environment as a whole. fn. 8 Furthermore, we can look at the way in which automated systems may contribute to discriminatory practices or systemic bias in the way we construct frameworks for production.

If we are to contextualise this within contemporary discussions regarding automation, we can find this notion of feedback embedded in frameworks that focuses on efficiency and optimisation. This is one narrative of robotics in architecture that has already been explored elsewhere in this book. However, it is important, and even essential to the discussion in this chapter, to realise that this is not purely about quantitative consequences, i.e. technical optimisation of a robotic system for economic reasons (as we have seen discussed in some earlier chapters) either in terms of saving time or saving material. It is also the qualitative – that which we cannot easily measure through the immediacy of data – that must be taken into consideration, too. For example, as Jelle Feringa and Asbjorn Sondergaard wrote about in their past work with Odico Formwork Robotics, the quantitative and the qualitative should not be held in opposition, but viewed as complementary. This way we can think about issues such as what Feringa and Sondergaard describe as “transferability” – or scalability, agility, performance and “degrees of freedom” – or how to enable “new opportunities in design, either by relaxing existing constraints or by offering a new way to explore previously uncharted design space.” fn. 9

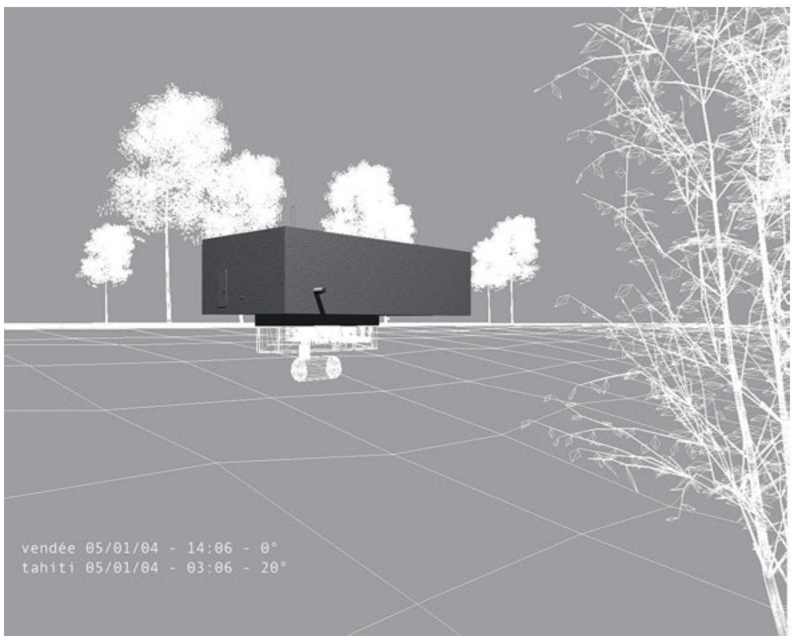
‘Superstudio, A Journey from A to B, 1969’. Illustration from ‘The New Domestic Landscape’ catalogue of MoMA exhibition, 1972 (photographer: Aldo Ballo). © 2019. Digital image, The Museum of Modern Art, New York/Scala, Florence

Liberation through Automation

It is impossible to discuss these issues without looking at their history within the discipline. If we understand machines as part of a framework taking into account quantitative outcomes and qualitative potentials, then we can look towards work developed by several designers, architects and thinkers in the latter half of the 20th century. Notably the founder of Massachusetts Institute of Technology's Media Lab Nicholas Negroponte, cybernetician Gordon Pask and the architect and educator John Frazer (most known for his work at the AA School of Architecture in the late 1980s and early 90s chronicled in the book An Evolutionary Architecture (1995)) were seminal in the way in which early notions of machine learning and big data were informing the ways in which technology was embedded, and later dissipated, into systems of communicating design solutions and potential opportunities. As Negroponte wrote in 1969 in "Toward a Theory of Architecture Machines", architects "cannot handle large-scale problems, for they are too complex; second, architects ignore small-scale problems, for they are too particular and individual." [fn. 10] According to Negroponte, machine-assisted architecture or architecture machines, "that can intelligently respond to the tiny, individual, constantly changing bits of information that reflect the identity of each [individual] as well as the coherence of the [whole]" [fn. 11] would liberate the designer. This could easily be transposed into Feringa and Sondergaard's thinking of facilitating projects through degrees of freedom – to discover new landscapes for, or forms of, architectural design. One could also assume that what Negroponte meant when he said this would result in more time for the architect to "do that which he really loves" [fn. 12] was that this could even mean time for leisure – e.g. for us, one of the outcomes of a fully automated society where robotics is dissipated into everyday life.

Embedding Robotic Systems

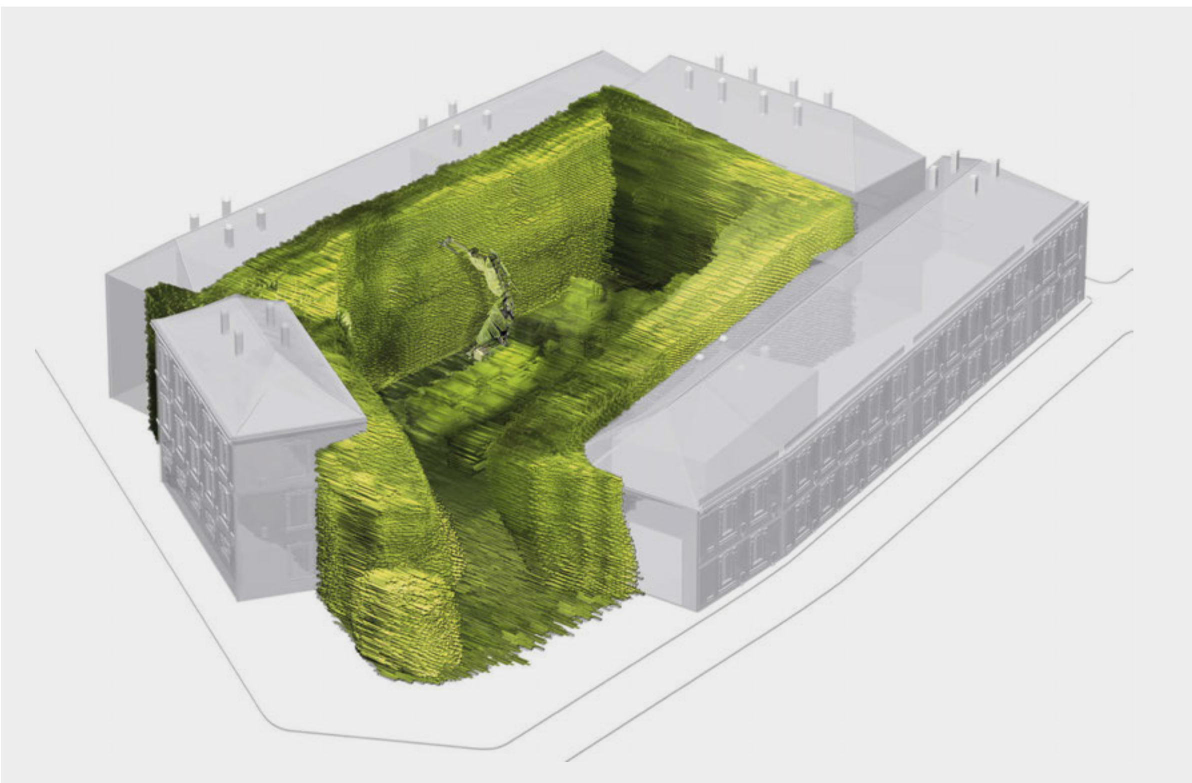
In 2012, the architect Francois Roche wrote that any approach to the socio-political status quo – in relation to the ways in which we make things (our tools and processes) and the products of those processes – needs to be extremely wary of being "eviscerated of any rebellious, not to mention alternative, hypothesis that would turn [their] talent into a tool for transforming the system." [fn. 13] If we are to evolve this logic, then robotics and automated systems should not be viewed only as fabrication devices. Instead, architects should embed robotics within architectural design and building processes, outcomes, and forms of inhabitation, thus amplifying the ways in which today's economic, political and social conditions can be reframed to project different, alternative world(s). The utilisation of robotics in this chapter is prospective, not retrospective – in the sense that they are not nostalgic, but assumptive of their future necessity to be at the centre of the way in which we work and live.

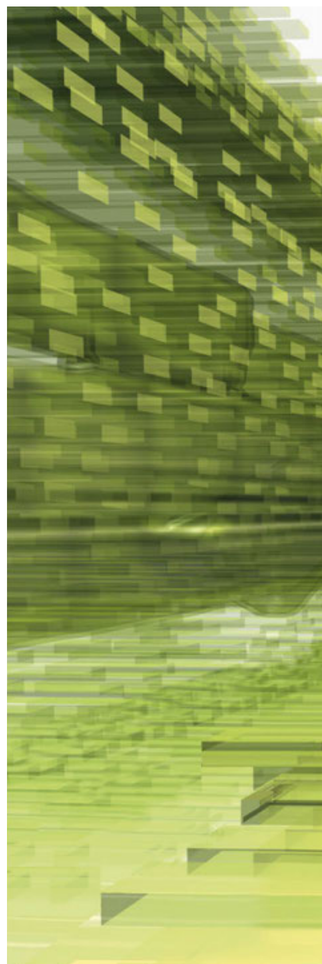


Winterhouse, Philippe Rahm, 2002

Attempting to do this has resulted in a number of different approaches: from more object-focused frameworks of production, to the physical manifestation of otherwise invisible, but experientially tangible environmental or climactic conditions, to projects more interested in pursuing the development of communication interfaces as a means through which architectural ideas are disseminated to, and engaged with, a wider public or participatory strategy. For example, Winterhouse (2002) by Philippe Rahm attempted to make a disciplinary problem out of the world between the traditional architectural elements of wall, floor and ceiling. Automated systems such as ventilation and heating became just as architectural as the material that constructed their boundaries.

Roche's work with R&Sie(n) (comprised of Roche, Stéphanie Lavaux and Jean Navarro), notably the project developed for the FRAC Orléans courtyard in France in 2006 titled Olzweg, attempted to shift the means of construction away from traditional understandings of what a building is. In Olzweg (2006), an animalistic automated machine lives in the courtyard, perpetually constructing an architecture of recycled glass elements. RFID-tagged visitors navigate with cellphones through the always-evolving building, "self-reprogramming and progressive[ly] [adapting] fn. 14 to the evolution of desires". fn. 15 In this work (and others since), R&Sie(n) presented a framework for architectural production that embedded a robotic system at its very centre, able to engage with the notion of both "transferability" and "degrees of freedom" as outlined above. If extrapolated from the micro to macro scale, the robotic machine of R&Sie(n) could easily be seen as part of a swarm of coordinated, autonomous robots assembling entire buildings or new material behaviours – such as Project Dom Indoors (2015) by Asmbld or Flight Assembled Architecture (2011–2012) by Gramazio & Kohler and Raffaello D'Andrea or Kokkugia's (Robert Stuart-Smith and Roland Snooks) research into swarm intelligence (ongoing) – from walls to



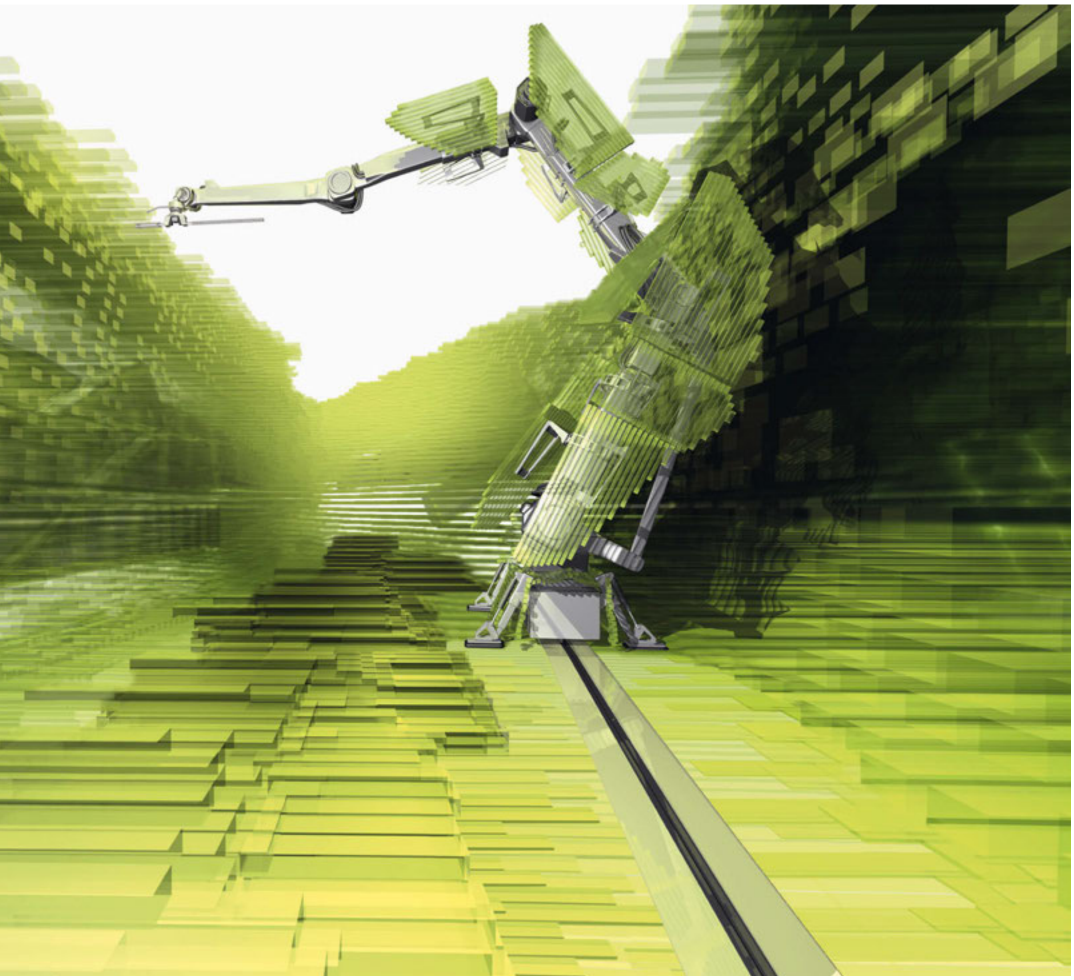


Olzweg, Frac Orleans, New-Territories/R&Sie, 2006 urban spheres, existing in equity (or inequity, as Roche points out in his reference to humans potentially "losing" themselves in the construction) with the humans that inhabit them. The consequences of projects such as these on an economic, social and political scale are very much aligned with the age of intelligence we are now operating within today, where "artificial" intelligence and human intelligence are intertwined, so much so that they almost exist in a gradient between one and the other.

But this is merely one way to frame the diffusion of robots into contemporary architectural design and building – sitting within the bounds of experimental disciplinary design research practice, as well as more object-driven. If we look to another narrative, we can see projects such as WikiHouse (2014–ongoing) that are, similarly, presented as a complete framework for architecture, but look at it from a different perspective: that of democratic, participatory and open-source architectural production, and primarily process-driven rather than design-driven. An online platform and repository for drawings and data, and portable and mobile robotic production in the form of CNC machines was designed to lower costs of materials, labour and other resources. Similarly, in the end however, the use of automated technologies to facilitate the project was perhaps less important than the actual dissemination and communication of the work itself.

Why We Automate

This leads us to the primary questions that the projects included in this chapter can be seen to address: If we automate, why should we? Why do we? How can these projects be, in their own way, part of the widespread change we saw Antoine Picon speak of in the beginning of this chapter? The title of the chapter – diffuse – hints at answers to these questions. The projects included here begin to move away from the notion of the physical robot towards a "networked" robot that is embedded, interactive and may show us something we do not know already about the built environment and the infrastructures – political, economic, social – that produce it. HoaxUrbanism (2017) by M. Casey Rehm (Studio Kinch) is probably one of the more unlikely inclusions in this book, as other work by Rehm



Olzweg, Frac Orleans, New-Territories/R&Sie, 2006 deals more explicitly with robotics. Yet HoaxUrbanism is the project in this chapter that most explicitly deals with the notion of non-human agency, as HoaxUrbanism is primarily research into graphics and machine-learning in relation to data and generative design and does not consider automation in an anthropocentric way. It is most closely aligned to the notion of the qualitative outlined above, thinking about the way in which data, and how the data's accessibility, degree of resolution and bias play a role in the way data is analysed, processed and harnessed in design. This notion of bias is important when considering the way in which robotic frameworks reflect social structures or our assumptions about space and place. In particular, Rehm's work trains neural networks to produce images projecting a world that seems to exist as it does only because of our own familiarity and anthropocentrism with these kinds of images themselves.

A clear line can be drawn between explorations looking at the collaboration of human and non-human agency in Rehm's work and Benjamin Bratton's notion of "The Stack", where we have emerging an "accidental megastructure, one that we are building both deliberately and unwittingly and is in turn building us in its own image." fn. 16 How do we make sense of these new, diffused and sentient architectures where humans and robots interact, influence and evolve one another? How do we deal with this new ecology of digital, robotic machines overlaid on top of our existing economic structures and frameworks?

Jose Sanchez's (Plethora Project) Common'hood (2019) takes the clearest critical, anti-capitalist position towards the ecology of robotic machines of the three projects in this chapter. Sanchez's work utilises this ecology to speculate on what a post-capitalist world may look like, one that does not privilege single anthropomorphised robots. Sanchez also investigates issues that are in Rehm's project, particularly the notion of how the availability of resources or data influences design outcomes but through an open-source video game. In Common'hood, players are invited to speculate on how an ecology of scarcity might look in an age of automation, with the constraints of automated fabrication tools embedded into the game. Sanchez's previous video game, Block'hood (2016), also explored similar themes, but on the scale of an urban neighbourhood, while Common'hood focuses on architectural outputs – houses or homes in particular. In Sanchez's work, users are enabled to take ownership of the means of automation, quite literally, for the benefit of constructing an ecology for the Commons, where users contribute to, and benefit from, participating in how, when and why the built environment is produced. This needs to be taken forward carefully however, as it draws from the notion of the "fab lab" critiqued in the Introduction and elsewhere in the book, where robotic machines are distributed to lay users for them to construct their own environments. The work challenges the current modes of governance that regulate and legislate our world, rethinking the ways in which the digital economy can play a role more equitable for all.

In Greg Lynn's RV Prototype House (2012), the incompatibility of today's Western homes with the finiteness of resources and intelligence of available architectural systems is explored. Inhabitation is projected on all surfaces of the house, forcing the body to continually act to keep up with the pace required to live in it. This project makes the immaterial that is present in the projects of Rehm and Sanchez super-present and tangible in its architecture. Automation in this project is present as a servant to the human body, with the architecture of the house taking care of its inhabitants, providing comfort measures. Automation here is almost domesticated. It is possible to connect this to the utilisation of smart technologies such as Nest or Amazon Alexa. The automated architecture of Lynn in this instantiation simultaneously extends our capacities to organise our environments and liberates the human body from the need to take care of itself or others.

Whereas the once-intangible dreams of science fiction used to exist on pages and screens, today they are diffused into every corner of our earth. Yet architects have had much more to do with the dreams and their representations than the ways that these dreams have come to life. What each of these projects helps to highlight is that ultimately, automation is a design problem, dealing with complex economic and political contexts. What kinds of frameworks is automation already embedded in or should be embedded in? At every stage of technological progress in automation, from the Industrial Revolution to today, it has enabled us to be more human and to live in a more equitable, democratic world. What kind of automation do we want? By highlighting these questions and contexts as issues, this book points out the vast and deeply challenging nature of automation in architecture beyond the techno-fetishistic, apathetic or purely artisanal. Automation is not something architects should shy away from, on the contrary: it is the most exemplary form of liberation we have in our arsenal today.

fn. 1 Antoine Picon, “Robots and Architecture: Experiments, Fiction, Epistemology”, *Architectural Design,* Volume 84, Issue 3, May / June 2014, 57.

fn. 2 Ibid.

fn. 3 John Maynard Keynes, “Economic Possibilities for our Grandchildren” (1930), *Essays in Persuasion,* New York: W.W. Norton & Co., 1963, 358–373.

fn. 4 Adam Greenfield, *Radical Technologies: The Design of Everyday Life,* Verso, 2018, 190–191.

fn. 5 Mario Carpo, *The Second Digital Turn: Design Beyond Intelligence,* Massachusetts Institute of Technology, 2017, 3.

fn. 6 Norbert Weiner, *The Human Use of Human Beings,* Da Capo Press, 1954, 13.

fn. 7 Mario Carpo, *The Second Digital Turn: Design Beyond Intelligence,* Massachusetts Institute of Technology, 2017.

fn. 8 Wiener writes about this notion: “The machine, like the living organism, is […] a device which locally and temporarily seems to resist the general tendency for the increase of entropy. By its ability to make decisions it can produce around it a local zone of organisation in a world whose general tendency is to run down” in Norbert Weiner, *The Human Use of Human Beings,* Da Capo Press, 1954, 34.

fn. 9 Asbjorn Sondergaard and Jelle Feringa, “Scaling Architectural Robotics: Construction of the Kirk Headquarters”, *FABRICATE 2016,* UCL Press, 2017, 266.

fn. 10 Nicholas Negroponte, “Toward a Theory of Architectural Machines”, *Journal of Architectural Education,* Vol. 23, No. 2 (March 1969), 9.

fn. 11 Ibid.

fn. 12 Ibid.

fn. 13 Francois Roche, *Log 25: Resistance,* Anyone Corporation, Summer 2012, 5.

fn. 14 Brackets added by authors.

fn. 15 See https://new-territories.com/welostit.htm. Accessed March 15 2019.

fn. 16 Benjamin H. Bratton, The Stack: *On Software and Sovereignty*, Massachusetts Institute of Technology, 2015, 5.

HoaxUrbanism, 2017

M. Casey Rehm, Studio Kinch

HoaxUrbansim is an attempt to engage in a contemporary design problem where the quantity of available information influencing the development of a project overwhelms the ability of the designer to engage with it intelligently without a massive reduction of fidelity. Neural networks have already proven capable of recognising patterns at a superior rate to humans in specific tasks. fn. 1 However, this project questions how they perform as generative design tools where the definition of success is less quantifiable.

HoaxUrbanism began as an exercise to explore the use of convolutional neural networks and related models within an architectural context. It became the testing framework for exploring the generative potentials and biases for various models, such as the Google DeepDream fn. 2 project which visually exposes the weights on image classification models, to models based on Cycle Consistent Adversarial Networks. fn. 3

The latter was ultimately used as part of the series of linked networks that produced the images presented here. The agenda was to produce networks which could generate fictional satellite images of anthropocentric development capable of fooling both human and machine evaluators.

Apophenia becomes an opportunistic device in generative applications of these tools. The model that produced these images features a tree structure, where a regional classifier trained on only three urban categories strides across images of uninhabited desert. Forced to identify each portion of the image in one of those three categories, the program then distributes the relevant pixels to a generative network trained on the corresponding classification. The result is an image expressing expected aesthetic parallels to satellite photographs of inhabited areas but with alien organisations and compositions. This arises from the insistence on the machine to register content where it does not exist, the difference in pattern recognition between the machine and the human and the biased curation by the artist of training data.

fn. 1 K. He, X. Zhang, S. Ren and J. Sun. *Delving Deep into Rectifiers: Surpassing Human-Level Performance on ImageNet Classification.* In ICCV, 2015.

fn. 2 Alexander Mordvintsev, Christopher Olah and Mike Tyka, “Inceptionism: Going Deeper into Neural Networks”, Research Blog, 17 June 2015, accessed 6 March 2018, https://research.googleblog.com/2015/06/inceptionism-going-deeper-into-neural.html.

fn. 3 Jun-Yan Zhu, Taesung Park, Phillip Isola and Alexei A. Efros. “Unpaired Image-to-Image Translation using Cycle-Consistent Adversarial Networks”, in *IEEE International Conference on Computer Vision* (ICCV), 2017.

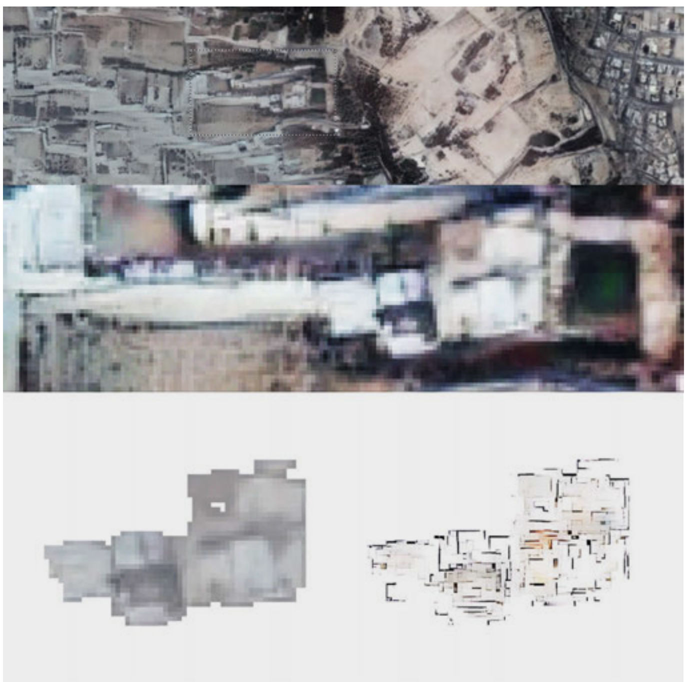
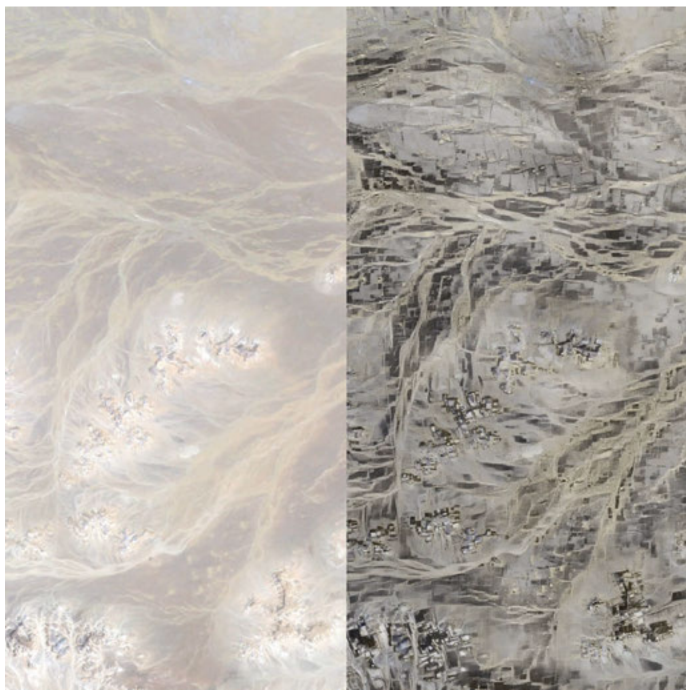
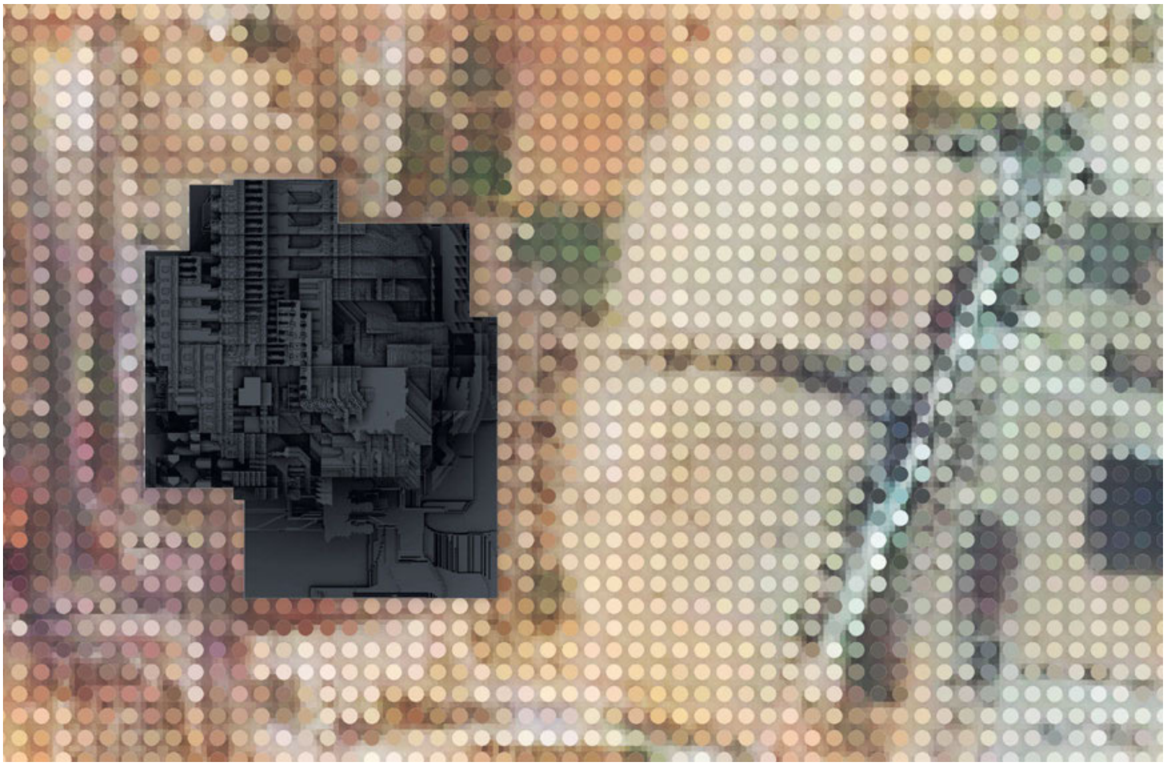


Image sequence showing the progression from house identified by regional classifier in the overall satellite image, roof plan of voxelized massing and finally internal plan slice trained on Mies Van der Rohe’s rural villas, HoaxUrbanism, Studio Kinch, 2017



Comparative detail sample of alternate satellite photograph and the resulting output of HoaxUrbanism. Original size – 40" × 80" at 200 dpi, HoaxUrbanism, Studio Kinch, 2017



Planar render of model exhibited at A+D Museum, Architecture, Architectural & Architecture exhibition, HoaxUrbanism, Studio Kinch, 2017

Comparative image of alternate satellite photograph and the resulting output of HoaxUrbanism V1. Original size – 40"x80" at 200 dpi, HoaxUrbanism, Studio Kinch, 2017

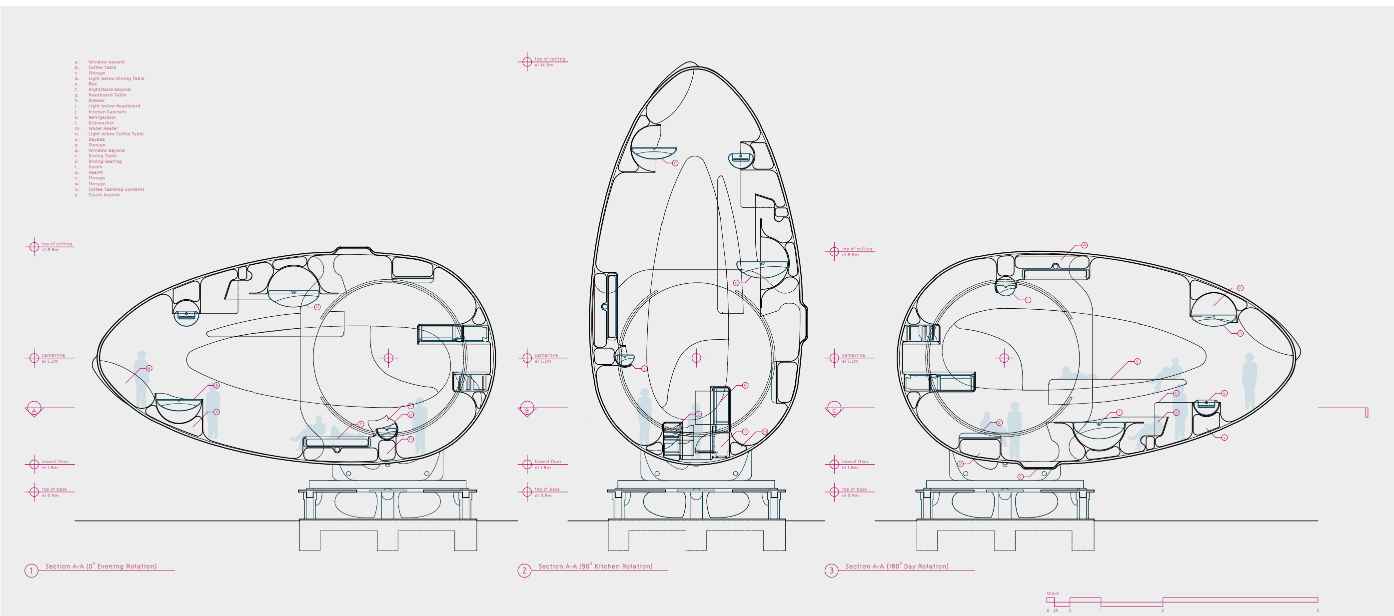
Perspectival render of a house generated through a CANN correlating voxel footprints of rural modernist houses with their massing, HoaxUrbanism, Studio Kinch, 2017

RV Prototype House, 2012

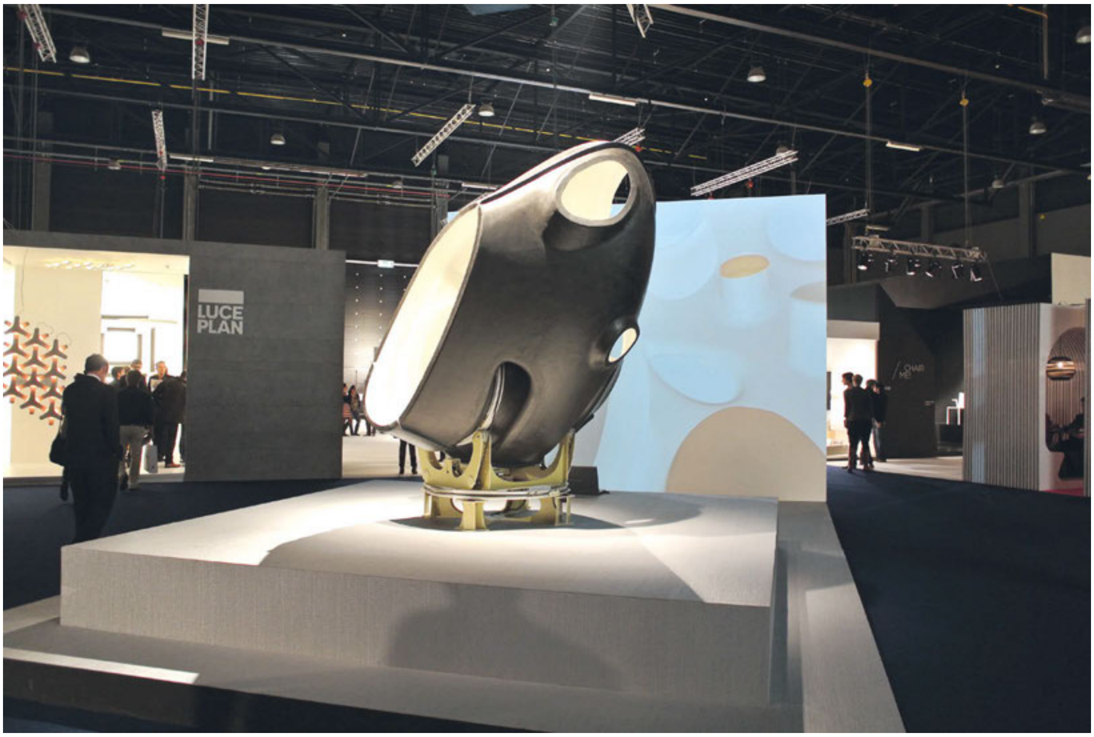
Greg Lynn, Greg Lynn FORM

Because of contemporary digital communication, entertainment and the intelligent control of machines, the world expects more from the physical environment today. Mobility and high performance must be calibrated with reduction in footprint and efficiency. The bespoke comfort of a one-of-a-kind specified automobile is merging with the living room couch and television where every place aspires to be a first-class flat-bed seat with colour temperature and intensity-controlled lighting, Internet access and entertainment on demand.

The RV Prototype brings intelligent movement and compact comfort to the living space as an alternative to over-inflated “McMansions” by reducing the footprint and material while also bringing the enthusiasm and activity of a theme park, a hamster ball, an exercise machine, a natural landscape or sporting equipment to the human living sphere. The living space does not move around you to make you comfortable, but instead you are rolled and must climb, tumble, traverse and spelunk across the ergonomic surface like a mountain goat, a Pilates disciple, a free-runner or wannabe Spiderman. Instead of a baronial interior of luxury materials, in order to be movable, the materials and construction methods of the RV Prototype replace masonry and steel with lightweight, high-strength cloth bonded to either a wood or cork core. To be affordable and socially responsible, the 60 m2 living space is distributed across the surface of the interior rather than just across the floor; thereby reducing the literal and energy footprint.



RV prototype in section at 0, 90 and 180 rotations © Greg Lynn FORM.



1:20 RV prototype in Kortrijk, Belgium, 2012 © Greg Lynn FORM

1:50 RV prototype on Kuka robots during filming © Greg Lynn FORM.

1:20 RV prototype CNC-cut EPS moulds awaiting carbon fibre lamination © Greg Lynn FORM.

Common'hood, 2019

Jose Sanchez, Plethora Project

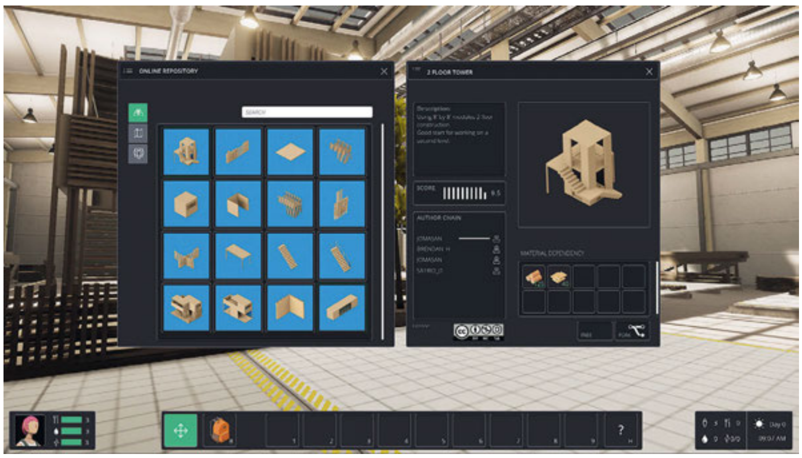
Common'hood is a simulated video game environment in which players embark on architectural design mediated by scarcity. The project seeks to explore the ecology of labour practices by inviting a player to engage with resource management to achieve creative building solutions. The game is also framed as an architecture social platform, where players are able to share creations with one another. Central to the project is the thesis that design can evolve if propagated freely within a social network. Closely following the guidelines of creative commons, Common'hood attempts to create a social repository of design parts that can be remixed by multitudes online.

Common'hood acknowledges that all software packages frame the view of the user and offer a design ontology. By making this bias evident, video games can establish a dialogue about the design paradigms we use for design and the social and economic implications they produce. Most software packages offer by default an environment of abundance, where creativity can run wild without regard to material costs, availability of materials or access to technology. By providing a simulation of a fabrication facility, Common'hood attempts to break this tradition. The game models the material and monetary requirements to acquire equipment, materials and knowledge, as well as the human cost that is required to operate and run a workshop.

By simulating an environment of scarcity, Common'hood is able to frame design as a creative challenge mediated by the availability of means. Design is considered a pattern of materials and knowledge that is contingent on manufacturing equipment and available skill and materials. Players are invited to share their design journey and learn from one another while maintaining ownership and authorship of their design contributions to a global community.

Gameplay, Common'hood, Jose Sanchez, 2019

Gameplay, Common'hood, Jose Sanchez, 2019



Online marketplace, Common'hood, Jose Sanchez, 2019

Gameplay, Common’hood, Jose Sanchez, 2019

Gameplay, Common’hood, Jose Sanchez, 2019

Gameplay, Common’hood, Jose Sanchez, 2019

Positions

Towards an Artificial Architecture: About Superintelligent Space

by Philippe Morel

> *"Just as there are odors that dogs can smell and we cannot, as well as sounds that dogs can hear and we cannot, so too there are wavelengths of light we cannot see and flavors we cannot taste. Why then, given our brains wired the way they are, does the remark, 'Perhaps there are thoughts we cannot think' surprise you? Evolution, so far, may possibly have blocked us from being able to think in some directions; there could be unthinkable thoughts."* [fn. 1]

> *"We have preconceptions about how an intelligent robot should look and act, and these can blind us to what is already happening around us. To demand that artificial intelligence be humanlike is the same flawed logic as demanding that artificial flying be birdlike, with flapping wings. Robots will think different. To see how far artificial intelligence has penetrated our lives, we need to shed the idea that they will be humanlike."* [fn. 2]

In the essay *The Doctors of Tomorrow Will Be Supercomputers,* published online at futurism.com at the very end of 2017, [fn. 3] Kyree Leary says doctors will be replaced by artificial intelligence-fed supercomputers. This is in line with many theorists and futurists including Kevin Kelly who, on a more "material" level, declared on 24 December 2012 in Wired: "*Even those areas of medicine not defined by paperwork, such as surgery, are becoming increasingly robotic. The rote tasks of any information-intensive job can be automated. It doesn't matter if you are a doctor, lawyer, architect, reporter or even programmer: The robot takeover will be epic. And it has already begun."* [fn. 4] For this last author, with whom I can only agree, if we are now at a *"point of inflection"* in the use of robots, it is because they have become intelligent machines. [fn. 5] Indeed, *intelligence* is the whole question …

Architecture has, just as science or comics, its own history of superlatives. Thanks to the eponymous exhibition of Pistoia, in 1966 a "Superarchitecture" (Superarchitettura) was added to the supercomputers and superheroes, which, according to its theorists, was an *"architecture of superproduction, superconsumption, superincitation to consume, supermarket, superman and super gasoline."* [fn. 6] As everyone knows, this superarchitecture has become, following Superstudio and Archizoom, a paradigm common to many other avant-garde groups which, according to a vanguard definition as *"dictatorship of reality",* have naturally developed an "architecture of reality". In fact, superarchitecture had incorporated the essential elements of the reality of an era, if not a computational environment just nascent or embryonic, whose signs appeared in the abstraction of grids and series, usually produced by hand on typewriters or in the coldness of otherwise narrative images. Computation appeared here and there but without the calculation being truly effective and in action; everything was as if it still belonged to reverie. There are some reasons for that. Firstly, the European industrial context of the time as well as the hyper-politicisation of the social sphere obviously played against an in-depth analysis of computation as well as the various but inevitable consequences of the quantitative and qualitative evolution of computers. Among the architects and researchers who were most interested in this issue, very few had the opportunity for direct access to the machines themselves, which were expensive and cumbersome and therefore extremely limited in Europe. Secondly, the visceral rejection of modernism contributed to a global discredit on a whole section of research inspired by science. "Proto-computational" architects and artists were often wrongly labelled as scientistic or naively progressive late modernist people, at the very moment when the concept of scientific progress was losing its authority. Like Leonardo Mosso in Italy, Francisco Javier Seguí de la Riva, [fn. 7] active at the Computing Center of the University of Madrid (CCUM) – an experimental space developed and financed by IBM from 1968, Jozef Jankovič in Czechoslovakia or Konstantinos Doxiadis in Athens, many researchers working around the possibilities provided by computers appeared either as positivists, or as anti-Marxists, or both … Finally, confronted with a formalism that rarely succeeded in renewing in-depth the codes of modernism and with the voluntary or forced departure to the United States or South America of many emblematic figures of the European avant-gardes prior to 1939, it was more judicious to turn to truly new experiments such as those of Pop Art or Conceptual Art than attempting to revive an outdated modernist art that became bourgeois and perfectly boring. Thanks to the history of art and, to a lesser extent, to the history of architecture of the 1960s and 1970s, we know that the United States has been both more active and more receptive to experiments conducted with computers, whether on (programming) languages themselves or by making instrumental use of these languages for the development of new forms and new spatial logics. The positive influence of great formalists of European origin such as Albers or Moholy-Nagy, many of whom had prestigious academic positions, the open-minded attitude of the most original American creators (R. Buckminster Fuller, J. Cage etc.), the relative absence of a monolithic stylistic school prior to the World War II against which it would have been necessary to take an equally monolithic opposite stance, as well as the political and economic incentives for a new science and a new aesthetic have unambiguously allowed the emergence of research in the United States for which a context of refusal of ongoing scientific policies, then associated with liberalism and imperialism, did not seem the most favourable… In any case, and perhaps because in the 20th century the question of knowledge was mainly addressed by positivist philosophers (including Viennese neo-positivists), superarchitecture has never been theorised in relation to *knowledge* itself: neither as architecture of intelligence nor as architecture of superintelligence. Now, in the age of supercomputers and strong artificial intelligence, it is useful to define the latter, at least in its broad outlines.

To theorise the architecture of superintelligence or at least *superintelligent space* would require in all rigour to describe in advance the concept of superintelligence with its variants. We will assume here that the reader is already informed on this question and if it is not the case we invite them to have a look at the most influential books and papers. [fn. 8] Nevertheless, as a very general reminder and before addressing the question of architecture, let us consider superintelligence as a radical increase in the general intelligence available, intelligence of machinic or human origin. If the hypothesis of the Singularity, [fn. 9] which we recall, is an empirical hypothesis based on historical facts, is based on the exponential increase of machine intelligence, there is nothing in theory against the possibility of a parallel increase in biological intelligence, for example through genetic engineering. In fact, it is quite probable that the intelligence of the future will be integral and that it will not recognise the usual natural vs artificial and physical vs biological distinctions; the possibility of synthesising DNA already demonstrates this. We are thus moving towards a distributed intelligence magma ("The" cloud…), which is to become the main component of any future architecture. An architecture massively generated by computational procedures – bringing together computation and data –, which will manifest itself through "superintelligent space". That this last one evokes various criteria, parameters and concepts associated with artificial intelligence – what exact type of machine learning, optimisation of algorithm etc. – is not essential, moreover its artificiality is not, as in the case of current AI, a purely technical artificiality. Superintelligence is not the collective intelligence of neo-operatives and classical humanists, but not being human does not mean it is simply mechanical. It is in fact *artificial,* in every sense of that word. It refers to the general hybrid intelligence in circulation, human and artificial, whose effectiveness comes from the very possibility of making symbolical and numerical computation through a prior formalisation, so thanks to its "artificialisation". As a result of this general formalisation and translation that flatten out the different forms of intelligence, it is an "artificial general intelligence" (AGI) that would have succeeded in integrating all the existing knowledge, giving birth to a concept of intelligence with both theoretical and practical efficiency, this further reinforcing the criterion of Turing universality while removing the anthropomorphism or biomimicry of the famous "Turing test". Indeed, the objectives of this test first defined to "demonstrate" the possibility of an artificial intelligence at least equivalent to human intelligence or, more modestly, to address criteria of intelligence, have been diverted to reintroduce a perfectly outdated anthropomorphism. In the field of architecture this anthropomorphism, indefensible and especially unusable, has been and is still regularly replaced by a biomimicry whose main asset, of a socio-political nature, is that it makes the *extra*-ordinary performance of computers and software ordinary and acceptable to the greatest number, including architects. It is not the least of the contradictions – I call it *The Social Paradox of Artificial Intelligence* – to see so many people, including those who need it, speak out against artificial intelligence, and by extension against the general artificial intelligence, in favour of a respectable natural intelligence; natural but rather badly shared… Beyond the fact that the affirmation "everything is in nature" makes us individuals of the Renaissance – so somewhat old … – it does not say anything about the level of "naturalness" we are speaking about. To say along with David Deutsch that all forms of intelligences, *in vivo, in silico* etc., obey the same laws of physics (including those of quantum physics) and can therefore be reduced to an artificial general intelligence (AGI) whose real understanding still eludes us, is obviously not the same as finding that humans are experts in logic or chess and that ants are experts in swarm intelligence… all the more so when humans are surpassed at chess. The neo-romantic sanctification of nature as it manifests itself in the most obvious way also does not provide a solid argument for our inclination to regard ourselves as the alpha and omega of "Creation" and intelligence, and this only because so far we are the sole species that have made use of rationalistic thought – in the service of a rational attitude and quite often also at the service of mass destruction … As K. Kelly reports it, "*we have preconceptions about how an intelligent robot should look and act, and these can blind us to what is already happening around us.*" It was also as early as 1980, certainly concerning a different problem of epistemology, what was recalled by R. Hamming summoning our own sensory limitations which should preserve us forever from any presumptuous attitude with regards to intelligence in general. In fact, neither with the most radical avant-gardes of the beginning of the 20th century nor later with Peter Eisenman, whose architecture is entirely directed to such an overtaking, did we really go beyond naturalism and mimesis. This for the simple reason that so far, we have never had to deal with an intelligence that, to take up the reactions to AlphaGo's victory against Lee Se-Dol from 9 to 15 March 2016, is external to us and manifests itself to us as an alien… So far, the history of machines has merely been a story of artefacts understood as quantitative extensions of our intelligence, if not more simply mere extensions of our bodies. What a rocket engine and a microscope – including electronics – have in common is that they both incorporate our knowledge – our theories – for our own quantitative extension. In one case we send our bodies, our tools, our theories or all three together into orbit, in the other we project our concepts at the heart of matter to confront them with what we suppose to be ever finer degrees of realities. The constant evolution and refinement of our theories obviously gives the impression of profound qualitative changes, but this is to be put into perspective. In fact, our logical presuppositions vary little or do not change, as evidenced by the fact that it is almost impossible for us to spontaneously consider laws and behaviours that do not appeal to classical dualism (the law of the excluded middle in logic). Our existence ultimately rests on an extremely limited set of rules forged from our daily experience so that we are able, as are mathematicians and physicists, for example, to free ourselves from them only at the expense of difficult and tedious efforts of abstraction, efforts that on a social level are clearly reserved for a minority of the population (although a greater number of people are capable of it) and for which we must really evacuate our direct intuition to the benefit of a *superior form of intuition* in which we do not really understand much… If we observe the evolution of logic, one finds how authentically qualitative changes are rare, as it took more than two millennia between Aristotle and G. Frege or between Aristotle and G. Boole for the logic to become truly modern. This logic as a product of *human* intelligence remains so deeply attached to that specific form of intelligence that it has developed only thanks to mathematicians whose intelligence appears precisely different, even *super*-natural, like a *superintelligence.* The current degree of abstraction of logic and, more generally, of mathematics and mathematical physics can no longer show advances in these disciplines as anything other than the productions of alien individuals who have succeeded in making a concept of intuition which completely escapes most individuals a material reality: in fact a cerebral faculty… Things happen not only as if the superintelligence escaped explanations – this is the case for some forms of strong artificial intelligence – but more radically still as if the phenomenology of superintelligence escaped all mental synthesis, in fact as it escaped phenomenology itself. We indeed perceive the effects of a new intelligence, but we do not grasp the rules, like young children in front of most phenomena or like adults who moved within a physical environment for tens of thousands of years without ever being able to faithfully reproduce most of its elements, at least before the invention of perspective. It is not uncommon to mention the Renaissance and the inventions of perspective and printing in the context of analyses of the current computational revolution, in general to bring the consequences of these 15th century inventions closer to the consequences of the invention of the computer. Nevertheless, if the inventions of perspective and printing have obviously marked the beginning of a new era, they may have even more embodied the end of a succession of previous eras and wanderings… Indeed, perspective, the prelude to a new vision of the world, was also the ordering – almost the final point – of a set of bodily experienced perceptions never translated into spatial thought through scientifically articulated concepts for which both an absence of representations and rigorous geometric constructions were crippling. There could be no real theory of space – everyone will understand that I consider geometric triangulation not as a theory of space but simply as a measurement – anterior to the invention of perspective for the simple reason that the foundations of an authentic understanding of space were lacking. How, in all rigour, can one theorise what one cannot even represent correctly? To better perceive what the absence of a general theory of space represented, it is enough to remember that for each region, country and tradition could be attached a specific representation stretching distances and planes, and deforming volumes and objects. With hindsight we wonder by what miracle a seemingly unachievable peak of geometric intelligence that appeared after long millennia is now within the reach of every child at the end of primary school. The task was authentically intractable, and the miracle consisted of a gradual evolution of our scientific methodology. If I come back to computation, although each interval of time of adaptation and time of adoption is always shorter, computation is socially comparable not to the invention of perspective as a "solution" – as the end of an era marked by the ordering of our perceptions – but largely to the appearance of what preceded, the Neolithic Period. Computation marks the entry into a new (post)history – *"the story of synthetic nature and Mendelised Campaign"* **fn. 10** – entirely geared towards a process of "cerebralisation" for which the tools of construction and action on the world are given to us; just as they had been given to the greatest number by a few individuals or creative peoples, and obviously by parents to children, the tools allowing tillage, breeding, the crossing of rivers or the manufacture of boats. All that makes it possible to realise the dream of logical positivism – a logical (re)construction of the world and even more radically its logical emulation, i.e. its *simulation* – is now here, under our eyes and available. Nothing prevents us from making use of it, no more to travel in the physical and information space than to develop a new architecture.

If, as mentioned above, the space of superintelligence or *superintelligent space* is massively generated by computational procedures, many will tend to consider from the angle of causality that we understand this space and that we have circumscribed it. Nevertheless, contrary to classical and modern rationalist projects – the global Rationalist Project – whose origin can easily be found, the computationalist project of a superintelligent space is based on the strict impossibility of going back to the beginning of computational procedures for which most of the operations escape us (technically and theoretically speaking *we will be able to run backward most of our computation,* but again I do not consider here computation on a uniquely technical level). Behind each petabyte of data are hidden other petabytes, behind each algorithm, approximation and rounding operation are hidden thousands, millions or billions of other algorithms, approximations and rounding operations. Behind each step of a computation within a sequence certainly finite but that gigantic dimensions make infinite with regards to any human faculty, hide trillions of trillions of discrete states that act as trillions of trillions of partial causes … If, mathematically speaking, beginnings and ends do exist in finite-state machines, these concepts are among many other certainties no longer of any practical use, since they completely escape all perceptual capacities and all phenomenology, the latter being a transitional and now achieved stage in the history of theories of perception. Finally, one will now have to accept *"leaving things without explanations".* It might, perhaps, be *"characteristic of a superior culture".* [fn. 11]

fn. 1 Richard Wesley Hamming, *The Unreasonable Effectiveness of Mathematics,* in The American Mathematical Monthly, Vol. 87, No. 2., Feb. 1980.

fn. 2 In *Better Than Human: Why Robots Will – And Must – Take Our Jobs,* 2012. https://www.wired.com/2012/12/ff-robots-will-take-our-jobs/

fn. 3 https://futurism.com/doctors-tomorrow-supercomputers/

fn. 4 Kevin Kelly, in *Better Than Human: Why Robots Will – And Must – Take Our Jobs.*

fn. 5 *"Here's why we're at the inflection point: Machines are acquiring smarts",* in Kevin Kelly, Op. cit.

fn. 6 *"La Superarchitettura è l'architettura della superproduzione, del superconsumo, della superinduzione al superconsumo, del supermarket, del superman e della benzina super."*

fn. 7 Javier Seguí de la Riva and Ana Buenaventura's research at the Computing Center of the University of Madrid (Centro de Calculos de la Universidad de Madrid), from 1968 to 1974, were recently presented at the first *Orléans Architecture Bienale (Biennale d'Architecture d'Orléans;* https://biennale-orleans.fr/).

fn. 8 Cf. Nick Bostrom, *Superintelligence: Paths, Dangers, Strategies,* Oxford University Press, Oxford, 2014.

fn. 9 Ray Kurzweil, *The Singularity Is Near: When Humans Transcend Biology,* Penguin Books, 2005.

fn. 10 Gottfried Benn.

fn. 11 Friedrich Nietzsche, *"It is necessary to leave things without explanations, it is the characteristic of a superior culture."*

Digital Fabrication, Materiality And Nostalgia
by Antoine Picon

Can the embrace of newness be completely forward-looking, without any kind of nostalgia or even regret for what once was and may no longer exist because of technological and social change? Many proponents of the digital revolution, beginning with the pioneers of digital fabrication and robotic building, want us to believe that they are impervious to this type of feeling, that nostalgia is absent from their minds. Of course, such undivided stances are rare, but the digital revolution has accustomed us to unheard behaviours and achievements. Could we have, perhaps for the first time, technological developments without even a trace of nostalgia?

I would like to argue here that such is not the case, that digital fabrication and robotic building are actually inseparable from a muted nostalgia that explains, among other things, why the figure of the craftsman and references to Victorian authors such as John Ruskin are present today in many writings on the current transformations of design and construction.

For that purpose, let me begin with what is probably one of the most salient features of the discourse held by designers involved in digital fabrication and robotisation: the notion of a different relation to matter, a difference related to a change in the conception of the natural world and its inherent dynamism. Matter is no longer seen as passive, but inherently animated. Its animation makes possible phenomena such as emergence that have proved inspiring for many designers. fn. 1

Such an attitude is linked to a change in the conception of the natural world, a change which has often been interpreted as the rise of a "new materialism". fn. 2 This new materialism challenges many traditional assumptions regarding nature and matter. For instance, emergence ignores the opposition between the inorganic and the organic, the geological and the biological. This opposition, which used to be a fundamental feature of the traditional understanding of nature, is challenged just like others such as the distinction between the material and the spiritual. Perhaps, more important for us is the distance that was supposed to exist between the concrete character of matter and the abstraction of human computation. The notion of "material computation" developed by researchers and designers such as Achim Menges or Jenny Sabin is based on the hypothesis that such a distance does not really exist. fn. 3

It is worth noting at this stage that computation is envisaged in a new perspective. It is no longer synonymous with the dry formulas of physical determinism evoked by French mathematician and physicist Pierre Simon Laplace in his famous Essay on Probabilities of 1814. fn. 4 Instead of framing a universe without surprise that seems analogous to a vast machine, computation becomes the inner principle of animation, the very life of the material world. It enables fabrication to plug into its dynamism. Rather than imposing arbitrary forms on a passive matter, digital fabrication should capitalise upon the spontaneous activity of matter, orient it rather than constrain it with unbound violence. An ideal of collaboration with matter permeates many approaches to digital fabrication. This ideal can refer itself to certain key aspects of Gilles Deleuze's philosophy, aspects that have been further elaborated by thinkers such as British anthropologist Timothy Ingold. For instance, in his book on making, Ingold criticises the traditional hylomorphic attitude that distinguishes between matter and form before evoking a new attitude in which making would be synonymous with growing matter, following its inner trends rather than moulding it from outside. fn. 5

In Ingold's eyes, the maker of instruments appears emblematic of this cooperation between matter, mind and hand. Using his critique of hylomorphism, I have passed almost imperceptibly from matter to the human subject that interacts with it. At first, matter may seem distant from the human subject. Matter is supposed to be completely exterior to subjectivity. But human subjectivity develops in constant and intimate interaction with matter. The 18th century French sensationalist philosopher Etienne Bonnot de Condillac gave a striking image of this interaction in his Treatise on the Sensations of 1754. Here, he describes a statue endowed with intelligence but deprived of the ability to feel. By successively investing it with a sense of smell, hearing, taste, sight and finally touch, the philosopher evokes its gradual awakening to the world of sensations and ideas. Each sense brings its own set of discoveries, but the real tipping point is when the statue acquires the sense of touch and thus discovers the existence of obstacles beyond itself that put up a resistance to it. Then, it realises at the same time that it possesses a body that interacts with them. The inertia and impenetrability of matter finally give it access to true consciousness.

Condillac's philosophical fiction could be generalised by saying that we actually co-construct our perception of the material world and our understanding of ourselves. Such a perspective should not be a problem for upholders of a "new materialism" that refuses Cartesian dualism between matter and mind.

In a series of articles and books devoted to digital architecture, I have chosen to call materiality this co-construction of matter and subjectivity. fn. 6 More specifically, I relate the rise of the digital in architecture to a more general shift in materiality, that is in the way we understand both matter and us. Here, I use the word materiality on purpose. For to say that something is material is not actually to attribute to it an entirely objective quality. Materiality denotes a kind of relation to certain objects and phenomena that seem to us more tangible than others.

Materiality depends upon our science, technology, social organisation and beliefs. For instance, with the automobile, acceleration has become tangible. It has changed the very perception of our body, empowering it, but also making it vulnerable. Materiality has evolved from one period to another. Ghosts were probably more material in the 19th century than currently, since one could photograph them, at least according to all those who believed in Spiritism. fn. 7 Today with the development of sustainability issues, sensors and computer simulation temperature gradients are becoming more material than they were before.

The digital age definitely marks a new episode in the evolution of materiality and this is not only because of digital fabrication. Instead, digital fabrication constitutes one of the expressions of the fundamental shift in our understanding of materiality, that is of matter, ourselves and the relations between the two. We see differently, for instance. We are used to zooming and de-zooming. With the development of digital encoding, we hear differently. We are becoming more and more used to augmented reality.

The post-human discussion represents an integral part of this shift. Just like our contemporary nature and matter seem to ignore the distinction between the non-organic and the organic, we operate as contemporary subjects that tend to be more and more composed of technological parts in addition to our flesh and bones.

Now, it is striking to observe how the new materiality of the digital age is permeated with the desire to restore a sympathy, perceived as long gone, with industrialisation, between the material world and ourselves. Before the industrial revolution, the distinction between the inorganic and the organic was porous. Making was more in sync with the spontaneity of materials. This is at least what we are to believe if we follow thinkers such as Timothy Ingold or Richard Sennett. This has led these authors to the project of renewing with what they perceive as the lost authenticity of craftsmanship. fn. 8

The notion of the designer as a craftsman permeates many digital enterprises today. It has found one of its paroxysmal expressions with Lars Spuybroek's book, The Sympathy of Things, which interestingly constitutes one of the privileged references of Ingold's book on making. fn. 9

The designer and maker as a craftsman places Ruskin as a possible theoretical forerunner of this perspective. Certainly some of Ruskin's ideas and perceptions, like his acute interest for the lines of force of nature, echo some of our contemporary interests. But there is at the same time something contradictory in this renewed interest in Ruskin and the almost total oblivion of the worker displayed in so many discourses on fabrication today fn. 10 Leaving this complex question aside, let me simply note that Ruskin's doctrine is permeated by nostalgia, and that nostalgia might very well colour the digital fabrication movement.

If nostalgia is indeed present in digital fabrication, what is it about? For one thing, nostalgia has been extremely present since the dawn of industrialisation. It has endured ever since as the counterpoint of the enthusiasm for modernity and modernisation, each time with the fear that some form of authenticity could become unattainable.

At the dawn of the industrial age, at a moment when the applied arts were beginning to manufacture semi-precious objects and ornaments, neo-classicism worried that the authenticity of Greek art could never be fully recaptured. The admiration for the Greeks is well-conveyed by the famous painting of Schinkel depicting Greece in its youth. Neo-classical artists such as the Danish sculptor Bertel Thorvaldsen are permeated by it. fn. 11

In a later stage of the modernisation and industrialisation process, Ruskin and many of his contemporaries became concerned by the lack of spirituality of the constructions of their time, as opposed to the genuine inspiration of the Gothic. According to the author of *The Seven Lamps of Architecture and The Stones of Venice,* the Gothic spiritual inspiration was especially noticeable in its ornaments, which bore the trace of the intimate association between hand and mind that characterised the medieval period. Ruskin was already critical of form as molded, which explains his hostility towards cast iron. Just like him, his disciples such as architects Thomas Newenham Deane and Benjamin Woodward tried to reintroduce the worker's hand in their buildings. For instance, this ambition played a key role in Deane and Woodward's design for the Oxford Museum. fn. 12

Early 20th century modernist architecture was nostalgic for a direct contact with nature, which it repeatedly tried to address with proposals such as the roof terrace that was meant to put man in direct contact with the elements and the interpretation of the modern city as a garden city. Both aspects play a fundamental role in Le Corbusier's architectural and urban projects. fn. 13

Can we ever escape nostalgia, especially when we are not completely aware of its looming presence? A first step towards this goal might be to understand better the source of our present-day concerns.

Contrary to what it claims through notions such as material computation, the digital era has extricated information from matter. It has separated the two and recorded information as a series of 0s and 1s that can be stored on all sorts of devices, regardless of their nature, before being re-injected into the physical world using laser-cutting machines and 3D printers. But it regrets this state of affairs and is longing to once again fuse information and matter. Digital designers and makers dream of restoring their lost unity.

On the one hand, the figure of the artisan that Ingold and Sennett hold dear has undoubtedly very little in common with the spirituality-infused one idealised by Ruskin. On the other hand, by seeking to be receptive to the forces that animate the physical world, it could well reflect a form of nostalgia linked to a feeling that it is difficult to avoid a rift between the information that designers manipulate and the matter to which it is applied.

Now, nostalgia is not necessarily a bad thing, despite its reputation. To a large extent, this reputation was due to the modernist stance and its systematic repression of a feeling that was nevertheless looming in the background of so many of its key proposals for buildings and cities. Nostalgia is not necessarily an irrational regret of the past that paralyses the desire for innovation. It can be actually linked to the desire to recapture and reinvent.

Nostalgia for the antique and the apprehension to never be able to equal the constructive prowess and the refinements of the Romans spurred the Renaissance to innovate in every direction, from technology to art and architecture. The Renaissance saw itself as a reinvention that presented all the characteristics of the new. After all, Renaissance buildings, such as Brunelleschi's Pazzi Chapel in Florence or Bramante's Tempietto in Rome, were almost never literal copies of the antique.

When trying to be more self-aware or autoreflexive from a disciplinary point of view, it is probably better to acknowledge the presence of nostalgia side by side with the desire to disrupt the extant state of things that are actually inseparable from it. Digital fabrication and robotic building might gain additional lucidity on what they try to achieve from recognising its presence.

fn. 1 Michael Weinstock, *The Architecture of Emergence: The Evolution of Form in Nature and Civilisation,* Chichester, John Wiley & Sons, 2010.

fn. 2 Manuel DeLanda, *A Thousand Years of Nonlinear History,* New York, Zone Books, 1997, Sanford Kwinter, *Far from Equilibrium: Essays on Technology and Design Culture,* Barcelona, Actar, 2007, Diana Coole, Samantha Frost, *New Materialisms: Ontology, Agency, and Politics,* Durham, London, Duke University Press, 2010.

fn. 3 Jenny E. Sabin, Peter Lloyd Jones, *LabStudio: Design Research Between Architecture and Biology,* New York, Routledge, 2018.

fn. 4 Pierre Simon Laplace, Essai *philosophique sur les probabilités,* Paris: Veuve Courcier, 1814, p. 2, English translation by F. W. Truscott and F. L. Emory, New York, Dover, 1953.

fn. 5 Tim Ingold, *Making: Anthropology, Archaeology, Art and Architecture,* London and New York, Routledge, 2013, p. 22.

fn. 6 Antoine Picon, "Architecture and the Virtual: Towards a New Materiality?", *Praxis: Journal of Writing+Building,* n° 6, 2004, pp. 114-121; Antoine Picon, *La Matérialité de l'Architecture,* Marseilles, Parenthèses, 2018.

fn. 7 Martyn Jolly, *Faces of the Living Dead: The Belief in Spirit Photography,* London, British Library, 2006.

fn. 8 Tim Ingold, op. cit., Richard Sennett, *The Craftsman,* New Haven, Connecticut, Yale University Press, 2009.

fn. 9 Lars Spuybroek, *The Sympathy of Things: Ruskin and the Ecology of Design,* Rotterdam, V2 Publishing, 2011.

fn. 10 We have discussed this issue in Antoine Picon, "Free the Robots!", *Log,* n°36, Winter 2016, pp. 146-151.

fn. 11 See on this question Jean Starobinski, 1789: *Les Emblèmes de la raison,* Paris, Flammarion, 1979, especially p. 112.

fn. 12 Peter Anthony, John Ruskin's Labour: A Study of Ruskin's Social Theory, Cambridge, Cambridge University Press, 1983, Eve Blau, *Ruskinian Gothic: The Architecture of Deane and Woodward, 1845-1861,* Princeton, Princeton University Press, 1982.

fn. 13 Adolf Max Vogt, *Le Corbusier, the Noble Savage: Toward an Archeology of Modernism,* Cambridge, Massachusetts, MIT Press, 1998.

Appendix

Authors

Design Computation Lab (DCL) is a research laboratory established in 2017 and located at The Bartlett School of Architecture, UCL that has quickly established itself as a world-leader in the development of computational design and fabrication methods for automation in architecture and design. DCL is directed by Mollie Claypool, Manuel Jimenez Garcia, Gilles Retsin and Vicente Soler whose shared expertise as architects, designers, theorists and roboticists includes a wide range of creative design technologies and applications, such as robotics, software development, manufacturing, product development, open-source platforms, 3D printing, user interaction, pre-fabrication/modularity, automation and augmented reality. The work of DCL has been widely featured in the architecture and design press and it has been exhibited internationally. The work of DCL is held in the collection of Centre Pompidou in Paris, France.

Mollie Claypool is an architectural theorist, historian, critic and educator. She is a Lecturer in Architecture at The Bartlett School of Architecture, UCL, where she is Co-Director of Design Computation Lab and History and Theory Coordinator in MArch Architectural Design. She led award-winning MArch Architecture Unit 19 from 2012-2018. Her work looks at the history and theory of digital design, computation and automation in architecture, as well as the economic, social and political implications of new technologies on architectural production.

Manuel Jimenez García is the co-founder and principal of madMdesign, a computational design practice based in London and co-founder of Nagami Design, a robotic 3D printing fabrication company located in Avila, Spain. His work has been exhibited worldwide. He is a Lecturer in Architecture at The Bartlett School of Architecture UCL, programme director of MSc Architectural Computation, Co-Director of Design Computation Lab, runs Research Cluster 4 (RC4) at the MArch Architectural Design and curates Plexus, a multidisciplinary lecture series based on computational design.

Gilles Retsin runs a young award-winning London-based architecture and design studio, Gilles Retsin Architecture that works with the newest technologies to explore smart, efficient, and sustainable forms of beauty. Trained in Germany, Switzerland and the UK, Gilles Retsin has 10+ years of experience working internationally on high-profile projects. He co-founded the Design Computation Lab at The Bartlett School of Architecture and is currently a Lecturer in Architecture at The Bartlett School of Architecture UCL, where he is Co-Director of Design Computation Lab, Programme Director of MArch Architectural Design and together with Manuel Jimenez Garcia and Vicente Soler, leads Research Cluster 4 (RC4).

Vicente Soler consults and lectures as a specialist in computational design and digital fabrication. He currently teaches at the MArch Architectural Design and MRes/MSc Architectural Computation programmes, at The Bartlett School of Architecture (UCL), co-directs Design Computation Lab and offers support for computation and robotics. He has developed a software for the programming and control of industrial robots – Robots – that is widely used in architecture schools and other institutions worldwide.

Contributors

AiBUILD is a London-based company founded by Daghan Cam and Michail Desyllas developing artificial intelligence and robotic technologies for large-scale additive manufacturing. Considering additive manufacturing the core technology for achieving a sustainable environment and a highly efficient on-demand economy, they work with a network of innovative clients, partners and investors to bring disruptive autonomous large-scale 3D printing technology into a wide range of industrial applications, with the goal to make manufacturing easy, smart, sustainable and affordable.

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Mario Carpo is Reyner Banham Professor of Architectural Theory and History, the Bartlett, University College London. Carpo's research and publications focus on the relationship among architectural theory, cultural history and the history of media and information technology. His Architecture in the Age of Printing (2001) has been translated into several languages. His most recent books are The Second Digital Turn: Design Beyond Intelligence (2017), The Alphabet and the Algorithm, a history of digital design theory (2011); and The Digital Turn in Architecture, 1992–2012, an AD Reader.

Brandon Clifford is an assistant professor at the Massachusetts Institute of Technology and the director and co-founder of Matter Design. As a designer and researcher, Clifford has received recognition with prizes such as the American Academy in Rome Prize, a TED Fellowship, the SOM Prize, the Design Biennial Boston Award and the Architectural League Prize for Young Architects & Designers. Clifford is dedicated to re-situating abandoned knowledge of the past into contemporary practice. This work continues to provoke new directions for digital design.

Design Computation Lab (DCL), established in 2017 at The Bartlett School of Architecture, UCL, is a world-leader in the development of computational design and fabrication methods for automation in architecture and design. DCL is directed by Mollie Claypool, Manuel Jimenez Garcia, Gilles Retsin and Vicente Soler whose shared expertise as architects, designers, historians and roboticists includes a wide range of creative design technologies and applications, such as robotics, software development, manufacturing, product development, open-source platforms, 3D printing, user interaction, pre-fabrication/modularity, automation and augmented reality.

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Gramazio Kohler Research, led by Professor Matthias Kohler and Professor Fabio Gramazio at ETH Zurich, has been at the forefront of robotics and digital fabrication in architecture since its inception in 2005. With their robotic laboratories and work that ranges from prototypes to buildings, they have inspired architects and researchers alike to explore the capacities of industrial robots as universal tools of the digital age. Projects such as Structural Oscillations for the Architecture Biennale in Venice, Flight Assembled Architecture at the FRAC Centre Orléans, Rock Print for the Chicago Biennale, the Sequential Roof for the Arch_Tec_Lab at ETH Zurich and more recently, the DFAB HOUSE, have contributed to the group's recognition as global leaders in in the field of digital and robotic fabrication in architecture.

Michael Hansmeyer is an architect and programmer who explores the use of algorithms to generate and fabricate architectural form. He has exhibited at museums and venues including the Museum of Arts and Design New York, Palais de Tokyo, Martin Gropius Bau Berlin, the Gwangju Biennale and Design Miami/Basel. His work is part of the permanent collections at the Centre Pompidou and FRAC Centre. He has taught architecture as visiting professor at the Academy of Fine Arts in Vienna and at Southeast University in Nanjing, and as a lecturer at the CAAD group of the Swiss Federal Institute of Technology (ETH) in Zurich.

Greg Lynn is the founder and owner of Greg Lynn FORM. He is also the CEO of Piaggio Fast Forward. He won a Golden Lion at the Venice Biennale of Architecture and represented the United States in the American Pavilion at the Venice Biennale of Architecture twice. He received the American Academy of Arts & Letters Architecture Award and was awarded a fellowship from United States Artists. He is an o. Univ. Prof. Arch. at the University of Applied Art Wien and a Professor in the Department of Architecture and Urban Design at UCLA. He taught at Columbia University for more than a decade, was Professor of Spatial Conception at the ETH Zürich, Davenport Visiting Professor at Yale University from 2000–2016 and Visiting Professor at Harvard GSD for the academic year 2017/18. He is the author of nine books.

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Philippe Morel is an architect and theorist, co-founder of EZCT Architecture & Design Research and initiator and founding CEO of the large-scale 3D-printing corporation XtreeE. He is currently an Associate Professor at the École nationale supérieure d'architecture Paris-Malaquais, where he heads the Digital Knowledge department. He was previously a Design Tutor at the Bartlett School of Architecture, UCL. Prior to this he taught at the Berlage Institute in the Netherlands and at the AA. His long-lasting interest in the elaboration of a theory of computational architecture is well expressed in his numerous essays, projects and lectures.

Odico Formwork Robotics is a pioneering formwork technology developer. Using proprietary solutions, it manufactures formwork for the construction and wind turbine industries. Its solutions enable an extended capacity to produce complex, architectural geometries that would otherwise be costly to realise, quickly and cost-effectively.

Antoine Picon is Professor at Harvard Graduate School of Design GSD. Trained as an engineer, architect and historian, Picon works on the history of architectural and urban technologies from the 18th century to the present. Four of his books are devoted to the transition from early-modern societies to the industrial era: French Architects and Engineers in the Age of Enlightenment (1988 and 1992), Claude Perrault (1988), L'Invention de L'ingénieur moderne (1992) and Les Saint-Simoniens (2002). With La Ville territoire des cyborgs (1998), Picon began to investigate the changes brought to cities and architecture by the development of digital tools and digital culture. Three of his recent books deal extensively with this question: Digital Culture in Architecture (2010), Ornament: The Politics of Architecture and Subjectivity (2013, Smart Cities: A Spatialised Intelligence (2015).

M Casey Rehm is a designer and algorithmic consultant based in Los Angeles, where he is the head of the multidisciplinary practice Kinch. He received an MSAAD from Columbia University in New York in 2009 and his BArch from Carnegie Mellon University in Pittsburgh, Pennsylvania, in 2005. He is currently a full-time faculty member at SCI-Arc where he teaches design studios and seminars in programming and robotics in design.

Jose Sanchez is an architect, programmer and game designer who is currently an Assistant Professor at USC School of Architecture in Los Angeles. He is the director of the Plethora Project, a research and learning project investing in the future of online open-source knowledge. He is also the creator of Block'hood, an award-winning city building video game exploring notions of crowdsourced urbanism. He has taught and guest lectured at several renowned institutions across the world, including the AA, the University of Applied Arts Vienna, ETH Zurich, The Bartlett School of Architecture, UCL and the Ecole Nationale Supérieure D'Architecture in Paris.

Patrik Schumacher is an architect and architectural theorist, serving as Director at Zaha Hadid Architects. He studied architecture at the University of Stuttgart and at the Southbank University in London, as well as philosophy in Bonn and London. In 1999, he received his PhD in Cultural Sciences from the University of Klagenfurt. Schumacher has been teaching at various architectural schools in UK, Continental Europe and the USA since 1992, and has been a co-director of the DRL at the AA School of Architecture since 1996. He has published numerous articles and the two-volume Autopoiesis of Architecture (2010).

Zoey Tan, Claudia Tanskanen, Qianyi Li, Xiaolin Yin were students in Design Computation Lab in 2016 –17 with the project INT: Robotic Building Blocks.

Ivo Tedbury is CEO of Semblr Technologies and a designer based in London, specialising in relative robotics for architectural construction. Ivo recently graduated from MArch Architecture with Distinction at the Bartlett School of Architecture in Unit 19, and was awarded the Ambrose Poynter Prize, Sir Andrew Taylor Prize, the Bartlett School of Architecture Medal, and the Imagination Bursary in Year 4. He previously completed a BSc in Architecture, also at the Bartlett, with First Class honours and winning the Fitzroy Robinson Drawing Prize.

Justin Werfel completed his PhD at MIT in 2006, developing algorithms to allow swarms of simple robots to autonomously build user-specified structures. His postdoctoral work included further exploration of collective construction at Harvard SEAS, work on the evolution of cooperative and altruistic behaviours at the New England Complex Systems Institute and cancer modeling at Harvard Medical School/Children's Hospital Boston.

Maria Yablonina is an artist, researcher and designer working in the field of robotic fabrication with a focus on custom, task-specific machines for making. Currently Maria is a research associate and doctoral candidate at the Institute for Computational Design and Construction at the University of Stuttgart. With a strong interest in robotics and digital fabrication techniques, she is currently focusing on exploring potential fabrication techniques enabled through introduction of architecture-specific custom robotic tools for construction and fabrication. Her work includes the development of hardware and software tools as well as complementing material systems.

Dr Philip F. Yuan (Professor, CAUP, Tongji University) is the founder of Archi-Union Architects, a Shanghai-based architectural design firm that has introduced a design style that is an amalgamation of global trends and local, traditional Chinese architecture. From this stems the low-tech digital fabrication method – Digital Tectonics – which merges the concepts of tectonic construction and ecology through a parametric design process combining digital technology and craftsmanship. Archi-Union's projects have been reported by international and national architecture media, including T+A, UED, UA, Arquitectura Viva, Abitare China, AD China, Dezeen and Archdaily.

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