ARUP

Designing with Digital Fabrication

ABOUT FORESIGHT

Foresight, Research and Innovation is Arup's internal think-tank and consultancy which focuses on the future of the built environment and society at large. We help organisations understand trends, explore new ideas, and radically rethink the future of their businesses. We developed the concept of 'foresight by design', which uses innovative design tools and techniques to bring new ideas to life, and to engage all stakeholders in meaningful conversations about change.

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COVER IMAGE

A bricklayer increases his precision using Fologram's AR Goggles to assemble a high-performance complex form wall.

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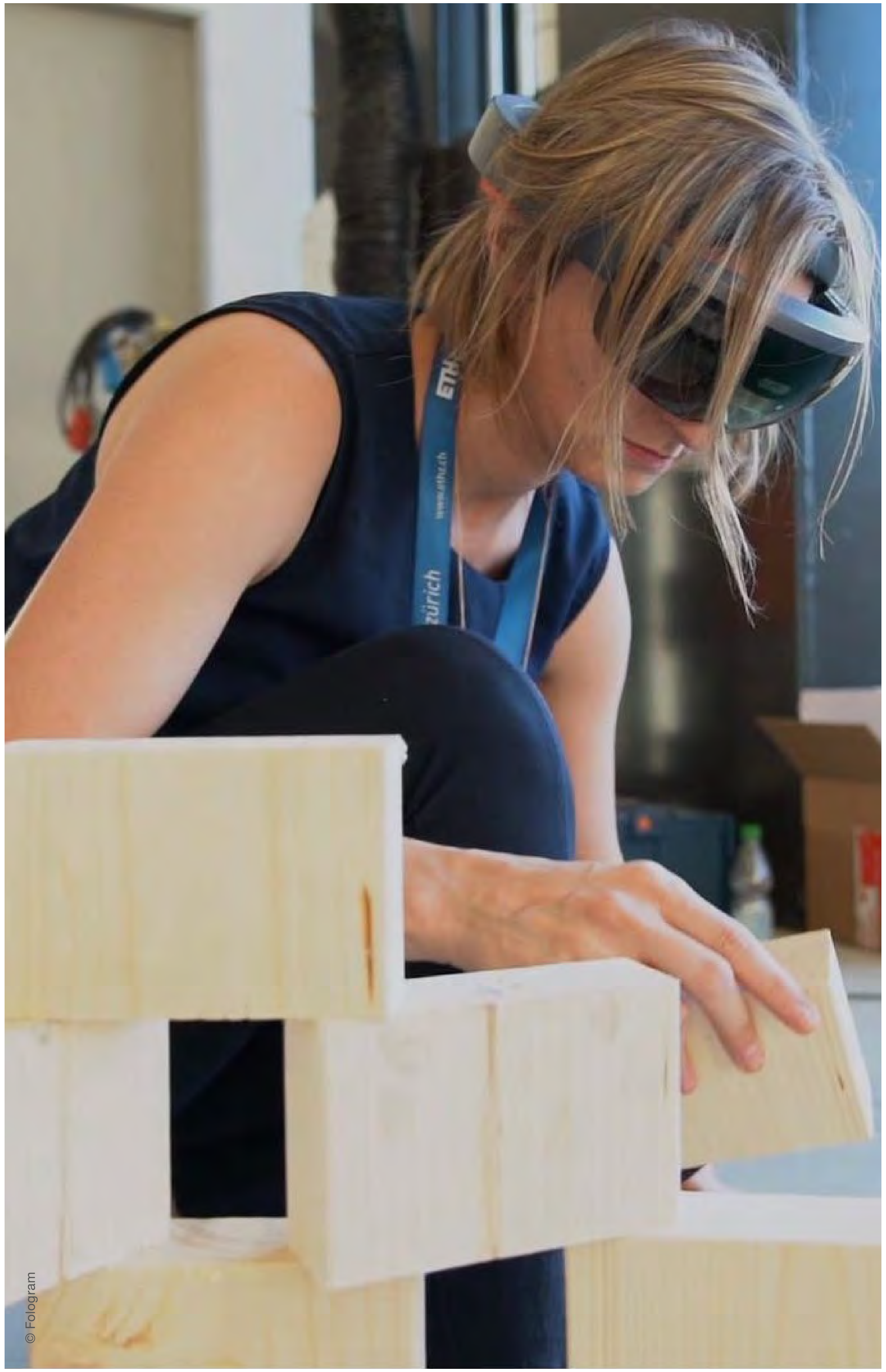

Foreword

FIONA COUSINS
Arup Fellow

No matter where they are in the world, the best designers work with the people who will make their work. Manufacturing and construction processes present designers with constraints and opportunities, influencing the kinds of materials that can be used, the shapes that can be formed, and the cost of making the work.

We have taken a close look at digital fabrication in this report, reviewing and explaining this fast-moving world. The earliest digital fabrication techniques were pioneered about 50 years ago and their usefulness is now increasing rapidly, through development of the techniques themselves and through the changes inherent in the world's broader digital transformation. These changes are enormously exciting for designers opening up new possibilities with both new and traditional construction materials.

The changes are pervasive. Our ability to use organic materials is improved through digital scanning that assesses their strength and shape, followed by digital fabrication techniques that allow them to be formed accurately using robotic methods. Traditional construction materials can now be formed using additive fabrication methods, allowing the realisation of complex geometries, resulting from all kinds of design priorities: the optimisation of material use, the creation of specific forms or the need to accommodate existing conditions. Machine learning techniques are augmenting and superseding traditional programming to improve the ability of robots to form materials, and digitally controlled processes can achieve higher levels of construction precision than humans. The techniques themselves may create less homogeneous materials allowing for localisation of material properties.

Of course, not every technique is ready for use in commercial construction, and Arup has developed an assessment scale to allow us to evaluate readiness. We have also identified some key challenges that arise from the use of these new techniques: the need to provide quality control for additively produced materials and the slowness of construction codes to change.

The potential impact on our work is clear. We must familiarise ourselves with digital fabrication and then work with fabricators and contractors to make best use of the changes in materials, construction accuracy and ability to produce mass bespoke forms that these techniques variously provide.

COMPLEX BLOCK ASSEMBLY WITH AUGMENTED REALITY
An unskilled workshop participant performs complex assembly using Fologram's AR Goggles. (RobArch 2018, Robotic Fabrication in Architecture, Zurich)

Executive summary

The opportunities unfolding with digital fabrication not only demonstrate new techniques in full-scale pavilion fabrication, but also provide new methods to solve design, business and societal challenges. As Dr. Caitlin Mueller of MIT Digital Structures reminds us: "The built environment is a very bad performer. Digital fabrication makes structurally efficient forms economical to build."

In this context, the goal is maximum reduction of material and waste with minimum disruption to the traditional construction methods to ensure fast adoption. It is not to demonstrate another novel technique.

By enabling complex forms optimised for material and waste reduction, digital fabrication is a key enabler for our industry to meet growing global demand for more infrastructure and buildings while operating within an increasingly resource-constrained world.

Digital fabrication enables bespoke solutions, in addition to complex high-performance designs that are free from manual fabrication constraints including standardisation, simplicity and scale. Someday soon, designing and making decisions with only manual fabrication will become redundant and even detrimental.

This briefing note focuses on today's computer control of fabrication; it builds on our previous Arup Explores AI with Machine Learning briefing note and provides an alternative plausible future to industrialised construction and industrial application of robotics and only hints at the very lively future of digital fabrication.

By enhancing the human with precision, as opposed to replacing the human, digital fabrication has the potential of rehabilitating the strained relationship between human and machines.

To improve the communication between digital makers and designers in support of greater digital fabrication adoptions, we propose the use of three established measures (NASA's Technology Readiness Levels, US DoD's Manufacturing Readiness Levels and Gartner's Hype Cycle) and one of our own – Arup's Fabrication Autonomy Levels (FAL).

This briefing note covers additive, subtractive, formative and robotic assembly (digital fabrication techniques). It shows how they apply to concrete, steel, and timber as well as composites and biodegradables, and highlights techniques lost during the industrial revolution that have been revived through digital approaches. Others were found to combine the traditional and the new with incredible results.

The main advantages of additive techniques are the creation of new materials, an enhanced ability to create geometric complexity and the reduction of waste. Metal alloys or a concrete mix "on-demand" are some of the opportunities, although quality certification can be a challenge. Formwork or false formwork, powder bed, and direct extrusion with or without supports characterise alternative techniques and offer advantages and disadvantages: the ability to create different levels of geometrical complexity or the need for novel certification.

Subtractive techniques have a long history. Computer Numerical Control (CNC) routing, milling and cutting share a high level of maturity and have been around for decades. Removing from a material block doesn't require additional certification. However, subtractive techniques produce waste in abundance. In addition to standard material stock of plywood for concrete formwork and steel, subtractive techniques have been applied to raw materials including non-standard tree trunks and salvaged components.

Formative techniques covered are robotic cold metal forming, incremental sheet metal forming and emerging techniques of smart dynamic casting and bending concrete.

The digital transformation of construction re-emphasises basic design principles by freeing decision-making from the otherwise in-built constraints of traditional fabrication. This contrasts with the industry's traditional emphasis on designing for construction standardisation. With this transformation approaching, it's risky for designers to be inattentive to how fabrication is evolving as it renders their advice redundant and potentially detrimental. An increasingly redundant advice on the one hand designs for traditional manual onsite construction which is unsuitable for those clients that need to scale, and on the other designs for manual manufacture and assembly, a construction process suitable to scaling, but lacks optimisation of materials and waste reduction, flexibility and adaptability which are vital to work within the constraints of one planet.

Design and decision making are evolving:

- from manual to data-driven design;
- from standard to bespoke;
- from geometrically simple to complex and undulating or rippling;
- from simple assemblies of complex components to complex assemblies of simple ones;
- from repetitive to diverse and mass customized;
- from within tolerance to highly precise;
- from practice recipes to first principles.

And the implications aren't limited to design. The business of design, construction and fabrication is also changing: early adopting contractors are winning contracts well beyond their experience, while services such as standard steel design and construction have already become redundant in at least one project.

The digital transformation of construction allows us to manage uncertainty and offer a more agile process. De-risking clients' late changes is an additional opportunity the designer can offer with the digital transformation of construction, beside its primary values of increased productivity and reduction of waste.

Designing with digital fabrication presents new opportunities and helps attract talent. It gives contractors the chance to win an improbable contract – for example a complex hospital facility in a more developed country – and to manage clients' uncertainty, therefore extending their market to clients that aspire for better quality.

Possibly the greatest implications are for society. Digital fabrication enables complexity and diversity of form which has the potential to enhance resilience without compromising the ability to create at scale. Optimised forms save up to 80% of material yet at no increase in waste. Digital fabrication enables the effective use of unprocessed materials – for example tree trunks – and the reuse of non-standard salvaged components – for example timber blocks – directly addressing the increasing scarcity of virgin materials.

By enhancing the human with precision, as opposed to replacing the human, and by freeing design ideas from the constraints of mass production, digital fabrication has the potential to rehabilitate the strained relationship between humans and machines.

Designing free from the constraints of manual fabrication challenges the well- accepted best practice of design and decision making for appropriate manual construction, or appropriate design for local culture and capabilities. However, as we must share one planet, can we afford the luxury of making decisions based on local human construction skills?

In many parts of the western world – for example North America – the acute skilled labour shortage can be addressed by enhancing unskilled labour with computer control via tablets – think Uber – or, better still, via head mounted displays. From bricklaying to wiring complex assemblies in Boeing aircraft bulkheads, this approach not only solves the immediate shortages, most importantly without compromising design, but also has the potential to trigger a virtuous cycle of learning. After all, pilots are trained on flight simulators. It also has the potential to make construction an attractive option once again to younger generations.

What are the successful actions early adopters have taken that designers and decision makers across the industry can be inspired by? As an industry, how

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can we ensure that appropriate digital fabrication techniques are specified on projects? The likelihood of success when choosing a technique has technical, cultural and policy aspects. For example, powder-bed computer-controlled bonding of mortar enables more complex outputs, but computer-controlled extrusion is less of a departure from manual processes and the resultant materials are more readily certified.

In every region and market, designers and decision makers must assess digital fabrication's relevance to their clients' aspirations and its uptake by the industry.

This briefing note takes advantage of Arup's global presence and multiple design practices through the Arup Explores programme, as we gathered diverse techniques, understood implications and learned about successes in digital fabrication across the world.

We observed that Japan focuses on the "human in the loop" as it comes to terms with a history of industrial robotics that replaced humans and introduced process rigidity.

In the United Kingdom several contractors have purchased computer-controlled equipment including industrial robots. Digital fabrication co-exists alongside a government vision for construction focussed on Design for Manufacture and Assembly (DfMA), advocating standardisation and simplification for a largely indoor manual construction.

Australia seems to consider digital fabrication still to be in the realm of demonstrators and academia.

Europe has forward-facing experience in computer-controlled equipment and certifications of digital fabrication with DFAB HOUSE, MX3D bridge (see pages 22 and 53) and others.

In the US, academia is showing the art of the possible, for example with the complex assembly of simple parts of the NASA-MIT aircraft wing (see page 21) that addresses the challenge of circular design with digital fabrication, and clearly leading thinking on the future of digital fabrication, although detached from industry and the design and decision-making profession.

India has a high demand for new built environments. However, contrary to the US where labour exceed material costs, "in India, 70% of construction cost is material, not labour," reminds Dr. Caitlin Mueller who is designing low-cost highly optimised systems for mass housing there.

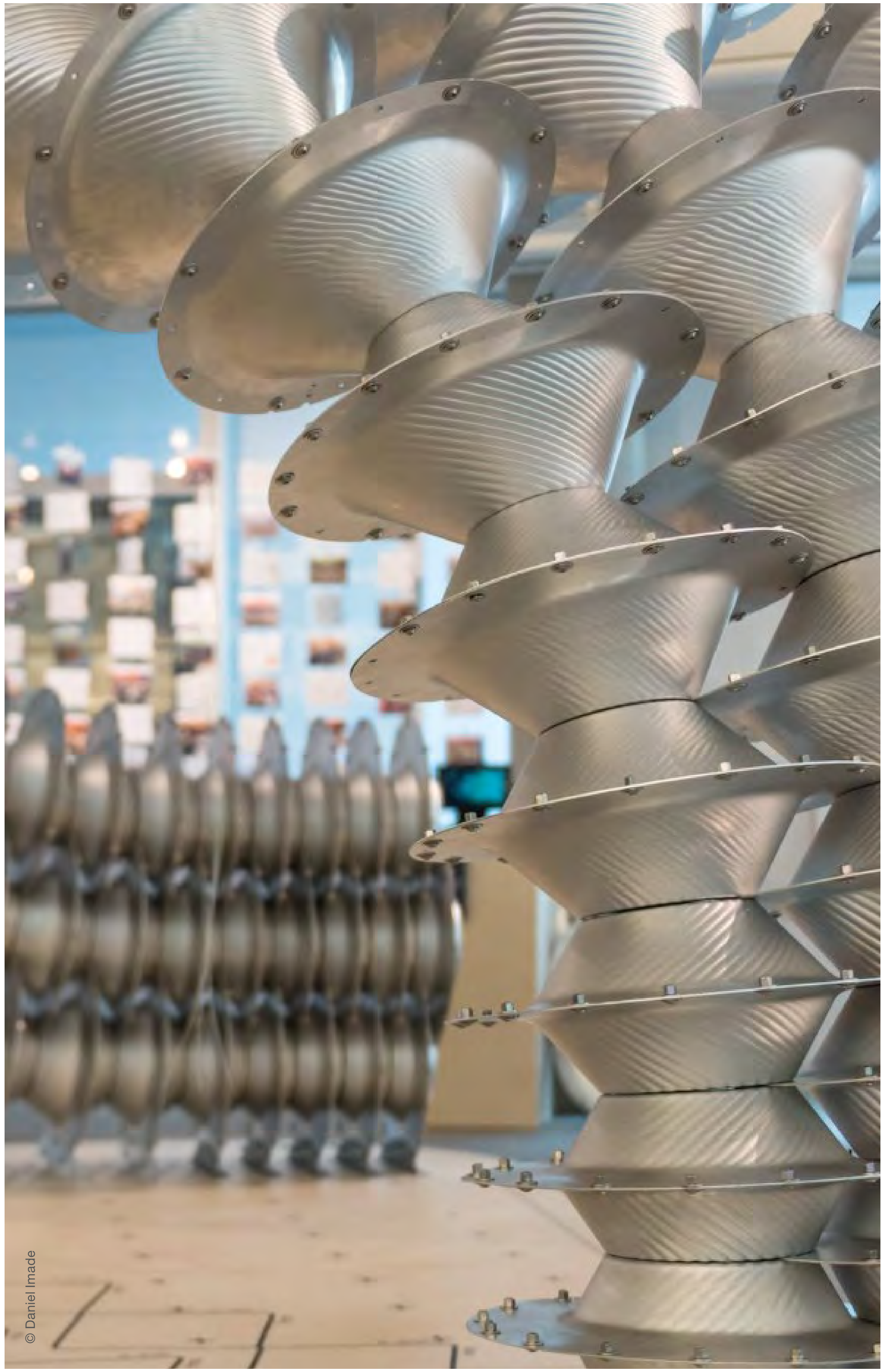
No matter where they work in the world, the best designers have always got close to makers. Grant Mattis of steel fabricator Feature Walters reminds us how the fabricator must fabricate what the designer designs, and the designer designs what the fabricator makes. Breaking this vicious cycle occurs through dialogue between fabricators and designers.

We observed early adopters participating at specialised conferences, conducting desktop studies, and taking journeys to learn from the experience of digital makers. They engaged with the innovation ecosystem, partnering with start-ups or sponsoring a PhD and engaging with students. Whether these early adopters practice digital fabrication as a hobby, create a demonstration or even register for a PhD, the return on the extra commitment is profound.

We recommend that industry professionals continuously educate themselves in the language and the culture of digital fabrication. The direction and speed of how this field is changing demands it.

It's time to begin your learning.

LIGHTWEIGHT FIBRE TESTING
Test setup at the ICD CCLab, University of Stuttgart, for elements of the BUGA fibre pavilion (2019).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Introduction

ALVISE SIMONDETTI
Explores Global Leader, Foresight

Digital transformation of the construction sector is inevitable. Indeed, it has already begun. William Gibson noted the future is already here, just unevenly distributed and there are some parts of the world where the transformation has already begun. The Arup Explores programme scoured the globe for the exemplars and lessons.

Digital fabrication has been around for decades, but designing with it is new. Digital fabrication was initially limited to demonstration projects such as the Daedalus Pavilion (see page 49). Recently, however, it has been applied to solve societal, industry and major project challenges, such as the completion of Sagrada Familia (see pages 25, 54 and 59). It supports the quest for excellence as our designers advise clients on the creation, fabrication and utilisation of their assets in the built environment.

It is seen as both a boon and a bane: it can answer novel client questions, win projects and reduce risk. On the other hand, its widespread adoption threatens to render the traditional advice of designers and project managers, referring to outdated construction techniques, redundant and potentially detrimental.

Three factors are driving digital fabrication: better computer control, growing demand for complex construction and the need for agility.

First, success with learned vs. scripted algorithms controlling computers has renewed hopes that robots can improve their limited performance and provide a viable alternative to a chronic skills shortage – and resulting increased labour cost – in construction. This is already producing an explosion of new techniques.

Second, the demand for built assets will continue to grow in the foreseeable future. Yet, resources are limited. Construction will exceed global resources of sand. Prices will soar. Digital fabrication enables form complexity with dramatically enhanced material efficiency yet limiting formwork waste.

Finally, a client's need for agility always comes into conflict with the rigidity of traditional industrial construction. The digital transformation of construction can help manage client uncertainty.

This briefing note gives a foundation about digital fabrication and the implications that this rapidly advancing field has on the industry. Our aim is to give the sector information to understand and decide how to engage with digital fabrication, appropriate to different markets, disciplines and geographies.

ROBOTIC INCREMENTALLY FORMED SHEET METAL
Metal components were uniquely customized for IncreMENTAL, an evolving sculpture in the exhibition *Drivers of Change: New forms of practice from The Bartlett School of Architecture*, 2019, Arup Phase 2, London. Arup in collaboration with BMADE, UCL, London

1 Definitions, assumptions and limitations

Ahead of describing the novel techniques that are providing exciting opportunities for designing with digital fabrication, a few guidelines are necessary for the reader.

The key blockages to the adoption of digital fabrication in design are the lack of communication between the communities of designers and makers, the absence of digital fabrication from official construction predictions, the emerging nature of data driven design and finally the rapid rate of change in the techniques.

Digital control of fabrication represents an alternative future of construction; however, we also acknowledge its connection with the official future of standardised and simplified industrial construction, or "indoor construction".

The intention of this briefing note is to enthuse and educate designers who have not yet embraced digital fabrication.

BUGA FIBER PAVILLION 2019
This structure of lightweight fibre composite was fabricated robotically by ICD/ITKE University of Stuttgart and FibR.

1.1 Definitions

All innovation can be classified along a set of defined stages. To improve communication between digital makers and designers, we propose the use of three established measures and one of our own inspired by the Self-Drive levels of autonomy:

- NASA's Technology Readiness Level (TRL)
- US Department of Defence Manufacturing Readiness Level (MRL)
- Gartner's 'hype cycle' to show acceptance by the public
- Arup's Fabrication Autonomy Levels to indicate the disruptiveness of each technique

1.1.1 TECHNOLOGY READINESS

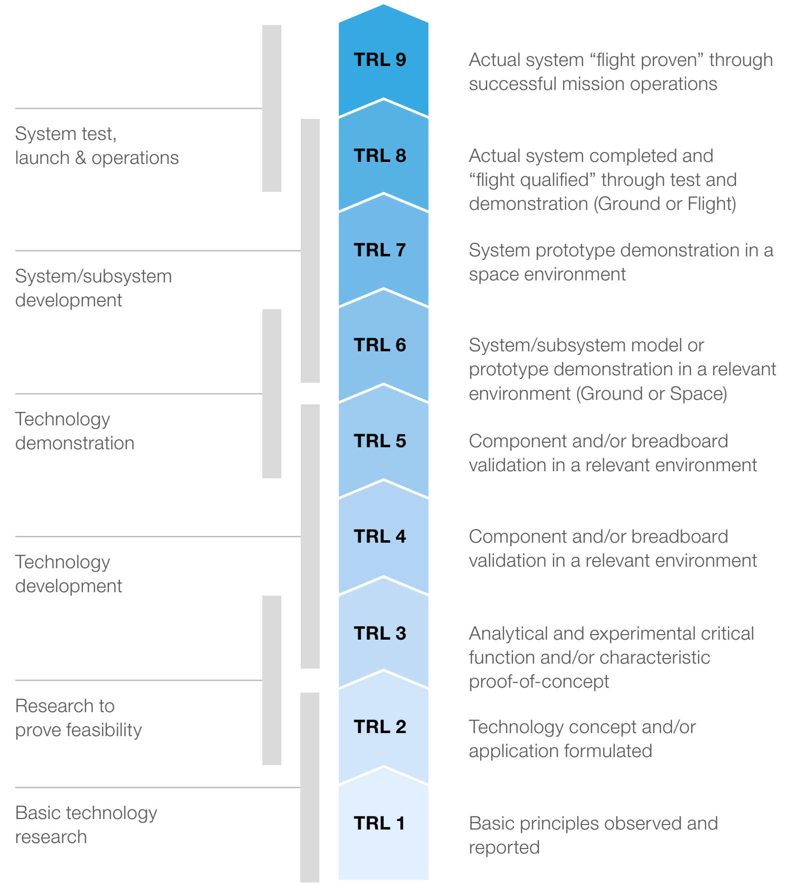
NASA's Technology Readiness Levels, often simply referred to as TRLs, provide a basis for discussion about a technology's maturity. The nine levels range from basic technology research to system, test, launch and operations.

For example, Cemex's "folding concrete" process (see page 40), currently developed by human hand, could clearly benefit from robotic precision, so falls into basic technology research (TRL 1 – scientific research is beginning). Whereas Mariana's KnitCandela Pavilion, developed in 2018 to prove the feasibility of knitted false-formwork for concrete (KnitCrete, see pages 28 and 74), would fall into technology development (TRL 3).

A great example of technology development demonstration (TRL 4-5) is Mesh Mould, an alternative to conventional formwork by Norman Hack while completing his studies within the Gramazio Kohler Research chair at ETH Zurich. Inspired in 2013 from a leaking formwork technique, Mesh Mould began as a false cage 3D printed in ABS plastic. An interdisciplinary effort between four Institutes at ETH Zurich - Technology and Architecture, Robotics and Intelligent Systems, Building Materials and Structural Engineering - enabled this project to develop rapidly to architectural scale.

Ultimately the ABS plastic was replaced with CNC cut and robotically welded rebar for reinforced concrete performance. The technique was executed on-site and in compliance to Swiss building codes in the 2019 demonstration home DFAB HOUSE in Dübendorf, Switzerland, by a new in-situ fabricator[1].

The US Department of Defence Manufacturing Readiness Level (MRL) is similar to NASA's TRL, but adapted to measure the readiness of manufacturing processes.



NASA'S TECHNOLOGY READINESS LEVELS (TRL)

US DEPARTMENT OF DEFENCE'S MANUFACTURING READINESS LEVEL (MRL)

1.1.2 TECHNOLOGY ACCEPTANCE

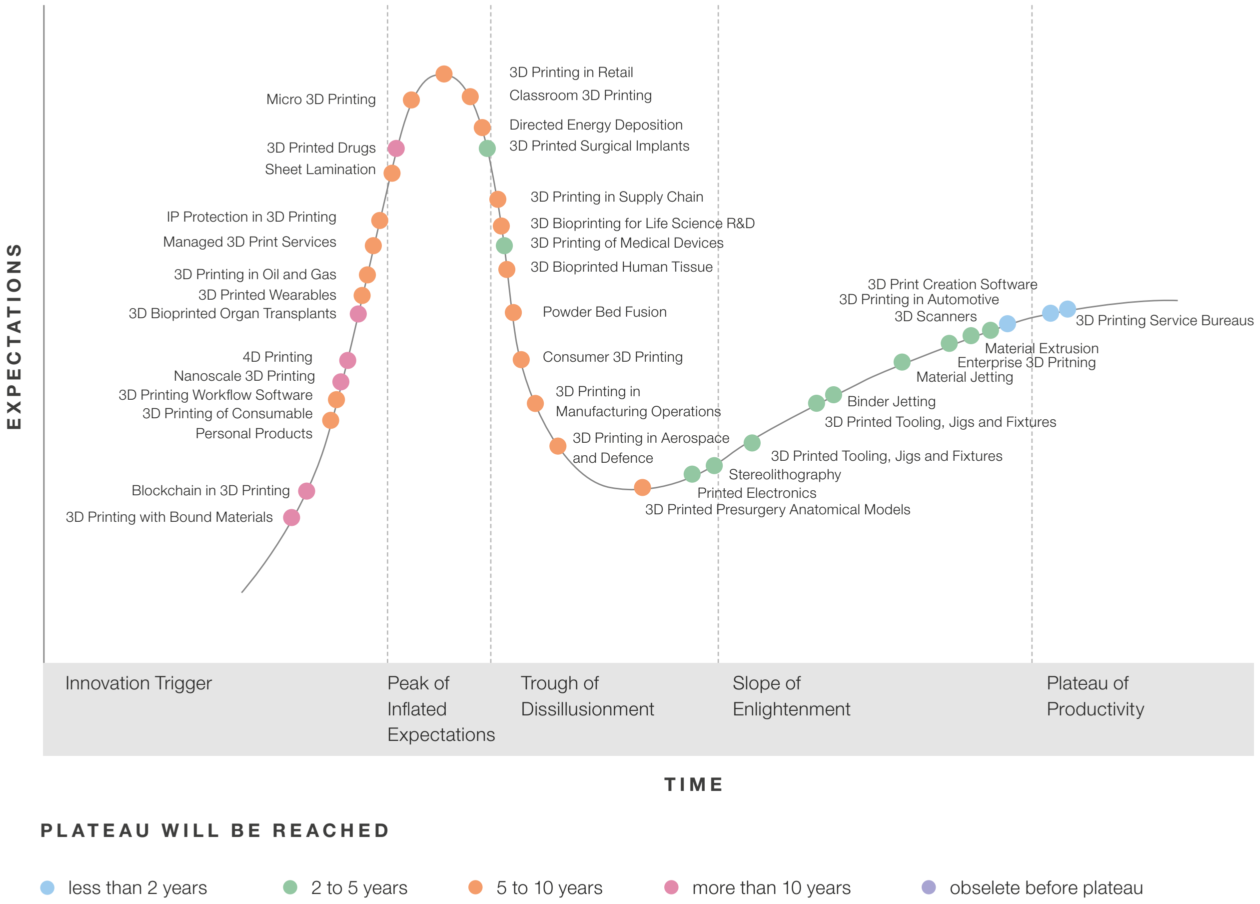
Gartner's 'hype cycle' measures, over time, the public's perception of new technologies, a key indicator for adoption. The cycle is driven by Roy Amara's view that says: "We tend to overestimate the impact of new technology in the short run and underestimate it in the long run."

The hype cycle evolves through a peak of inflated expectations to a trough of disillusionment, then a slope of enlightenment, until it settles on the plateau of productivity.

The first additive process, called stereolithography, was developed in the early 1970's. The term 3D printing originally referred to a multi-material developed at MIT by Professor Emanuel Sachs in 1993 and promised to change the world from printing food to steel, an inflated expectation. The public became disillusioned when they couldn't see tangible results and quality control could not be maintained. MIT Professor Neil Gershenfeld famously reframed 3D printing in 2014 as "the microwave of the kitchen of the future," or a small portion of the digital fabrication revolution. Today, 3D-printed aircraft partitions are in use.

The public acceptance might be misleading. For example, passive 3D printing techniques developed at MIT Self Assembly Lab are commonly perceived as the future of digital fabrication, but these are already used in industrial production.

GARTNER'S "HYPE CYCLE" FOR 3D PRINTING IN 2018



1.1.3 ARUP'S FABRICATION AUTONOMY LEVELS

The International Society of Automotive Engineers has defined levels of driving automation from the "hands on" Level 1 where the driver and the automated system share control of the vehicle (e.g. Cruise Control) to "eyes off" Level 3 where the driver must still be prepared to intervene when called upon by the vehicle to do so. Level 5 is "steering wheel optional" when no human intervention is required.

Inspired by these levels and a presentation by Daniel Prohasky, Swinburne Innovation Fellow at the Arup Explores event in Melbourne, Arup proposes six levels of digital fabrication autonomy.

Arup introduced these levels to facilitate discussion beyond the experts and enthusiasts. Different levels provide opportunities and freedom to the designer as well as challenges (for example with the certification of materials).

ARUP'S FABRICATION AUTONOMY LEVELS (FAL)

Level	Mode	Role of humans	Role of machines	Example
Level 5	Full autonomy – no operative nor supervisor mode	No human attention is needed off or on-site.	All construction tasks are conducted autonomously by learned robots with no operator off- or on-site.	Research at the Autodesk Robotics Lab at Pier 9 in San Francisco is aiming to demonstrate this mode.
Level 4	High autonomy – "minds off" on-site mode	No human attention is ever required for safety in factories. No more tasks are conducted by humans.	Few tasks are still conducted by scripted robotics under supervision and most are conducted by learned robotics autonomously.	MX3D bridge, the world first 3Dprinted bridge where the entire fabrication is conducted by machines.
Level 3	Initial autonomy – "eyes-off" mode	Only few tasks are conducted by humans, most are conducted by scripted robotics under human supervision.	Few tasks are conducted by learned robotics autonomously. Human attention is required only when called upon by the system.	Mostly scripted industrial robots used for creative applications that include a feedback loop. Ai Build robots use a feedback loop in their ABS plastic extrusion to speed up the fabrication.
Level 2	Partial automation "hands-off" mode	Most of the tasks are completed by humans.	Few fabrication tasks are handed over to scripted robotics off-site. Machines take over under full human supervision.	3D printing of concrete elements, CNC milling of a block of material.
Level 1	Augmented human "hands-on"	The operator is enhanced with super-human precision to assemble components by a mobile device (iPads), AR/VR or exoskeletons.	The machine is enhancing the actions of a human	Fologram, enables an unskilled operator to bend steel pipes in three dimensions by providing a target shape in the HoloLens augmented reality device.
Level 0	No automation	Construction including fabrication, transport and assembly is in the hand of humans.	No computer control	Any traditional technique such as manual casting of concrete

1.1.4 AN EXAMPLE APPLICATION

The designer might be considering the opportunity of designing with digital fabrication on a new project at scale for a client. In such a scenario it would be important for the techniques to be proven out of the lab, on site and approved by the local regulation.

Arup applied the four measurements to a sample of 15 techniques discussed in this briefing note. Only techniques that score at the top of the measurement scale might be suitable, and suitability might be limited to one country.

MEASURES OF TECHNOLOGY READINESS APPLIED TO SAMPLE TECHNIQUES

3DP: 3D printing

Technique name	Affiliation	Innovation date	Page reference	TRL	MRL	Hype cycle	FAL
Concrete 3DP	WinSun	2003		8	7	4	2
Powder Bed 3DP	D-shape	2009	28	8	7	3	2
Mesh Mould	ETH Zurich	2013	14, 29	7	10	3	2
Glass 3DP	MIT Mediated Matter	2014		6	7	1	2
WAAM wire arc additive manufacturing	MX3D	2014	22	7	10	2	3
ABS Plastic 3DP	Ai-build	2015	30, 32	7	10	2	3
Concrete Extrusion 3DP	XtreeE	2016	50	7	10	4	2
Smart Dynamic Casting	ETH Zurich	2012	42	6	10	3	2
Mobile concrete 3DP	Cybe	2016	27	7	10	2	2
Smart slab	ETH Zurich	2016	27	7	10	2	2
Learned robot	Autodesk	2017		1	1	1	4
Augmented Reality Goggles	Fologram	2018	39	7	10	1	1
KnitCrete	ETH Zurich	2018	28, 76	4	10	1	2
CurveCrete	Melbourne Uni	2018	41	4	5	1	2
Bending concrete	CEMEX	2019	40	2	2	1	0

READINESS LEVELS

Low High

1.2 Assumptions and limitations

Our note focussed on today's computer control of fabrication. Related areas include: data-driven design, the future of digital fabrication, the industrialisation of construction and industrial application of robotics.

1.2.1 DATA DRIVEN DESIGN

The key opportunity of digital fabrication to enable performance through complex form can only exist in a world of data-driven design. By this we mean design and decision making driven explicitly by data as opposed to implicit intuition. Due to the lack of availability of data sets and traditionally slow calculation methods, this is not yet a concern in practice. However parametric design, centralised BIM and IoT operations are well used by the industry already. In "Arup Explores AI + Machine Learning – Briefing Note"[2] (2016) data-driven design was discussed in depth.

1.2.2 INDUSTRIALISATION OF CONSTRUCTION

The official future of construction, according to the UK Government and the Association of Consulting Engineers to name a few in the UK, is industrialisation of construction[3]. Much of the academic research, driven by contractors' aspirations to increase productivity, safety and reduce the impact of construction, also focuses on this official future.

Industrialised construction began with the reconstruction that followed WWII, and is present in the US, Sweden, Poland, UK and Japan. According to the Modular Building Institute[4], today's market penetration varies from 3% of the US to 10% in Japan.

However, nearly all the so-called Industry 4.0 or Construction 4.0 or Industrialisation of Construction refers to indoor manual construction in factories and is not the focus of this study.

Indeed, as reported by McKinsey among others, robots have demonstrated success in "predictable environments and routine tasks" and are ill-equipped to respond to uncontrolled environments onsite as nearly all robots are programmed with an excruciatingly long list of commands to operate in highly controlled environments such as factories.

Factories may offer the best opportunity to introduce digital fabrication. Many leading contractors are rushing to add digital fabrication techniques in their processes and factories. For example, Canadian contractor PCL's new facility, PCL Agile, outside Toronto received their first computer-controlled cold-metal forming machine in 2019.

One pioneer in Industrialisation of Construction is Laing O'Rourke, with its world-leading facilities at Explore Industrial Park in Worksop, UK, operational since 2009. The facility has a high level of robotic fabrication, capable of producing an astonishing 10,000 m² of simple standard flooring and wall panels per week, but the demand for simple standard flooring and wall panels from the market is still lacking.

1.2.3 INDUSTRIAL APPLICATION OF ROBOTICS

The field of computer numerical control and robotics has developed in the past decades in two distinct applications: the industrial and the creative. Professor Ikeda from Keio University, speaking at Arup Explores in Tokyo, specifically pointed this out.

Industrial robots aim to replace humans in dull, dirty and dangerous tasks. They are geared to increase speed and productivity while decreasing costs. However, lower-skilled workers see industrial robots as simply taking away their work.

Using robots creatively, on the other hand, aims to augment humans by giving super-human precision and re-enabling complexity. By inviting Arup's sustainability advocate, Dr. Chris Luebkeman, to keynote their last Robotics in Architecture conference in Zurich in 2018, the leaders of this community sent a strong message. The ultimate driver behind the creative application of robots must be to enable better construction to support the UN Sustainability Development Goals, or in Arup's terms, supporting "A better way"[5]. We believe this has the potential to restore the relationship between human and machines.

This exploration is focussed on the creative field of application of computer control.

1.2.4 FUTURE OF DIGITAL FABRICATION

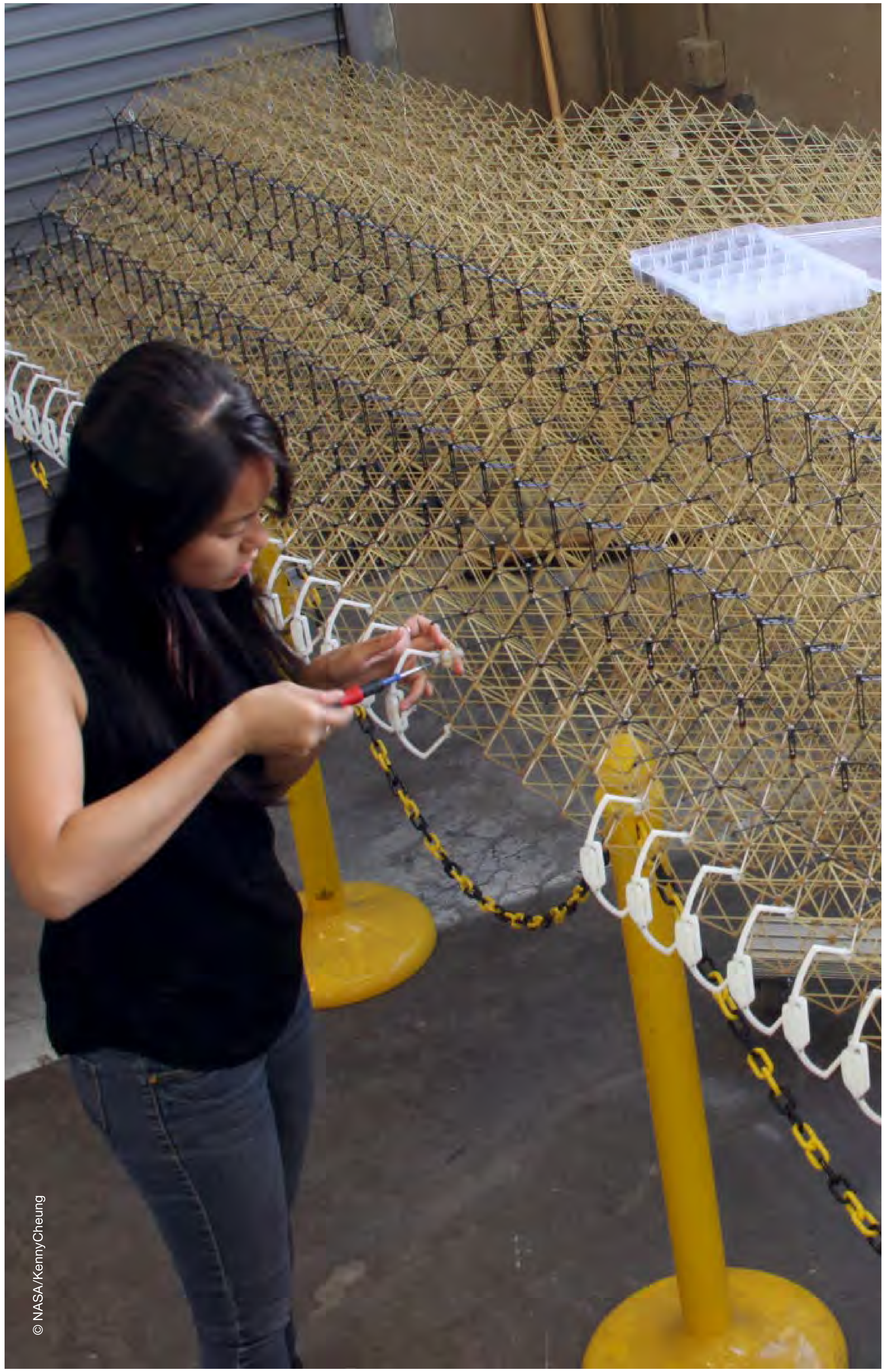
Our exploration only looks at digital fabrication today, but there is a very lively community exploring its future. Prominent examples include Autodesk Robotics Lab at Pier 9 in San Francisco which is exploring controlling industrial robots with learned as opposed to scripted code. MIT's Digital Structures group is researching retrofitting of non-standard parts or their connections, as is the AA School's Hooke Park campus. MIT's Self-Assembly Lab is looking into digitally designed passive assembly fabrication, MIT's Centre for Bits and Atoms is exploring the creation of digitally-controlled new materials all together, and MIT's Mediated Matter recently invented glass 3D-printing techniques.

This research must be taken into consideration by those involved with developing digital fabrication as opposed to designing with it. Designers should monitor techniques that achieved TRL 4 (validated in the lab) and concentrate on designing with those techniques that achieved TRL 5 (validated in a relevant environment).

One specific example of a time when knowledge of the future of digital fabrication is necessary would be when hard questions arise around reconciling high-performance bespoke components with their re-usability. An example of a high performance component that can be re-used is offered by MIT and NASA engineers with the complex assembly of simple versus the simple assembly of complex components. Engineers demonstrated a new kind of airplane wing[6]: a complex digitally-enabled assembly of many tiny identical components in stark contrast to the official future of simple manual assembly of few highly integrated, complex components that don't perform in terms of circular economy.

In section 4, Actions, we recommend that industry professionals educate themselves in the language and the culture of digital fabrication. The direction and speed of how this field is changing demands it.

We have evidence that clients, especially tech giants who are well versed in data-driven business, are bypassing our profession altogether, and exploring the future of digital fabrication directly with some of these leading academic labs. For example, Google has been working with MIT Self-Assembly Lab to create transformable meeting spaces that require no electromechanical systems to function and behave like a Chinese finger trap[7], with woven timber slats that telescopically appear and disappear. It is often said that construction hasn't changed in a hundred years and, naturally, the profession has adapted to it, however change has accelerated, and professionals and clients at the forefront of it are already ripping benefits. Our planet needs it.



FUTURE AIRPLANE WING
Shape-shifting airplane wing under construction, as assembled from identical sub-units. (NASA and MIT)

2 Techniques

What are the diverse digital fabrication techniques?

The first digital fabrication techniques emerged in the late 1960s, when computer numerical control (CNC) manufacturing equipment was developed. Most of the original CNC techniques were subtractive – milling, sawing and routing – and removed material off a larger block.

Soon afterwards the first additive process, stereolithography, was invented. This technique used a CNC laser to solidify a thin layer of photosensitive polymer precisely. The first solidified layer sits on a platform that is lowered by the thickness of each layer until the entire part is complete. In a generic additive process, the material is deposited layer-by-layer to form the part.

A robotic arm can accurately form sheet materials, as is the case with incremental sheet metal forming techniques. Bricks and other discrete material components can be robotically assembled in an additive fashion as well.

Today, additive, subtractive and robotic techniques are used on many materials, from concrete, steel and timber to composites and biodegradable materials. Even more exciting is that digital fabrication is re-invigorating and deploying traditional techniques lost during the industrial revolution.

Digital fabrication techniques are rarely used on their own. They are integrated to create hybrid techniques or sequenced with other CNC or manual ones.

WIRE ARC ADDITIVE MANUFACTURING
A 3D printed bridge being fabricated at MX3D in Amsterdam.

2.0.1 RE-INVENTED TECHNIQUES

The “Catalan Vault” technique, famously used by architect Antoni Gaudí, enables the construction – without scaffolding – of complex forms such as thin vaults with masonry tiles. It enables other work to occur underneath the vault while it’s being constructed, as well as reducing waste. This technique nearly vanished as the highly skilled workforce it demanded was decimated by the industrial revolution that favoured an unskilled workforce completing repetitive tasks.

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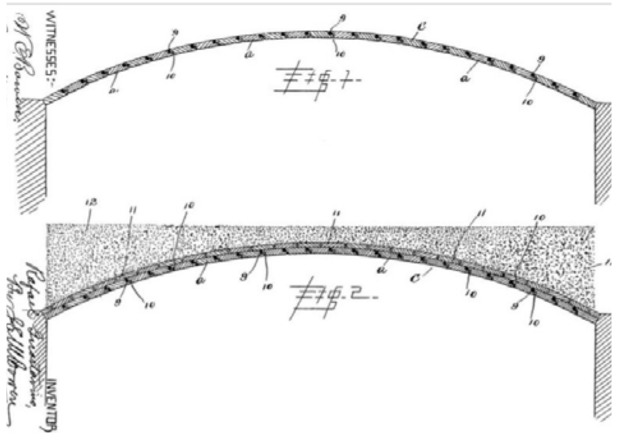
ENGLISH WHEEL
A pre-industrial revolution metal forming technique requiring highly skilled artisans.



CATALAN VAULT
Guastavino’s drawings for his patent No. 464,562 (1891) on the building of a vault without scaffolding by highly skilled artisans.

Another example is applying computer control to “English Wheel” sheet metal forming, a pre-industrial revolution labour-intensive technique that enabled complex high-performance forms without formwork.

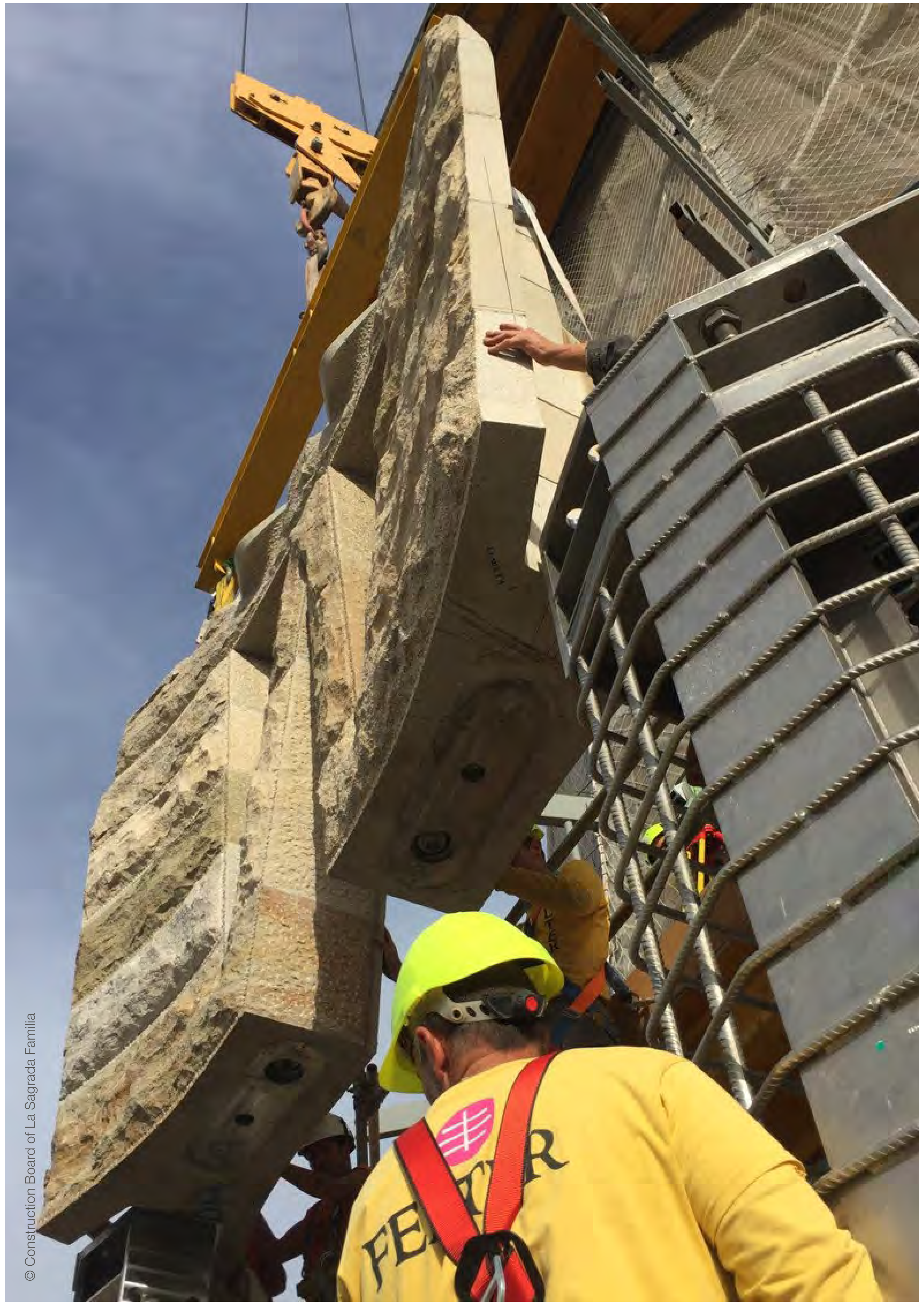
2.0.2 SEQUENCED HYBRID TECHNIQUES

Fifty years after their invention, subtractive, additive robotic forming and assembly techniques are entering construction. Hybrid techniques are often used where traditional fabrication supports digital technology to minimise the novelty of the process and related material quality certification challenges, yet achieves higher performance.

In practice, several digital fabrication techniques maybe sequenced. An example is Kreysler Associates’ fabrication of 700+ geometrically complex panels for the façade of the San Francisco Museum of Modern Art designed by Snøhetta with Arup. With 40 years of digital fabrication experience, Kreysler Associates used several rapid and cheap CNC hot wire cutting machines to “rough-cut” ruled surfaces for polystyrene formwork blocks. They later “fine-cut” the doubly curved surfaces with a slower, more expensive CNC-milling process. This sequencing of techniques saved a considerable amount of time on the project.

Another example of sequencing is in trials at Autodesk’s Tech Centre. This used an additive process for the “rough-creation” and subtractive CNC milling process for fine machining of the complex surface, taking advantage of the performance of both processes.

Finally, the prefabrication of stone for the completion of Sagrada Familia in Barcelona is a stunning example of digital techniques augmenting human fabrication. A high accuracy CNC process for cutting and drilling holes and pockets in stone is followed by traditional manual hammering of the visible surface to match the existing façade stone.



© Construction Board of La Sagrada Familia

HYBRID MACHINE AND MANUAL STONE CUTTING
Precisely machined stone blocks followed by manual hammering for the Sagrada Familia, Barcelona.

2.1 Additive

An additive process deposits material, or selectively sinters, or assembles layer-by-layer to form a part. The layers are generally horizontal. But, taking a page from nature, researchers are now looking into whether slices created parallel to the lines of stress can improve structural performance. This might result in improved and consistent additive material integrity, which is a key barrier to its adoption.

The major differences between additive techniques and traditional or subtractive techniques are:

- new material is created
- ability to create geometric complexity is enhanced
- the effect of subtractive technique limitation of undercuts is reduced
- waste is reduced

Creating new material generates opportunities and challenges. The key opportunity is creating metal alloys or a concrete mix "on-demand" with varying characteristics. The necessity to certify each hybrid material and in the case of varying mix, certify every part, is a major challenge. A "continuous certification" process is currently being piloted in 3D-printed metal parts for aerospace by Airbus.

The level of complexity varies according to the additive method used. Extrusion operates essentially as toothpaste and, when not printing additional supports, is limited in the geometrical complexity it creates by the cantilever angle. On the other hand, selective sintering (or selective bonding) techniques deposit an entire layer of material powdered across the "bed," and then selectively sinter only the material relevant for the part. This leaves the un-bonded remaining material to act as a support, which enables more geometrical complexity. Un-bonded material can generally be reused in the next printing, limiting waste.

Considering waste, subtractive techniques cut or mill the final design from a standard block of material and therefore produce great amounts of waste. Additive techniques don't. As mentioned above, some additive techniques create supports, generally in a different material. These supports must be removed once the part is completed, however support material can generally be fully reused.

2.1.1 ADDITIVE CONCRETE

There are three main techniques applied to concrete: printing formwork, or false moulds, extrusion of mortar itself and selective powder bed bonding. Most of the examples unless specified are at Fabrication Autonomy Level 2 – partial automation (see page 17). To achieve the complexity of form without incurring its challenges, 3D printing of mortar creates the complex geometry as a false mould, then further mortar is poured, and reinforcement is added in a traditional way.

Whereas extrusion and selective bonding don't require formwork, 3D printing formwork often involves recyclable materials such as wax, sand or even ice.

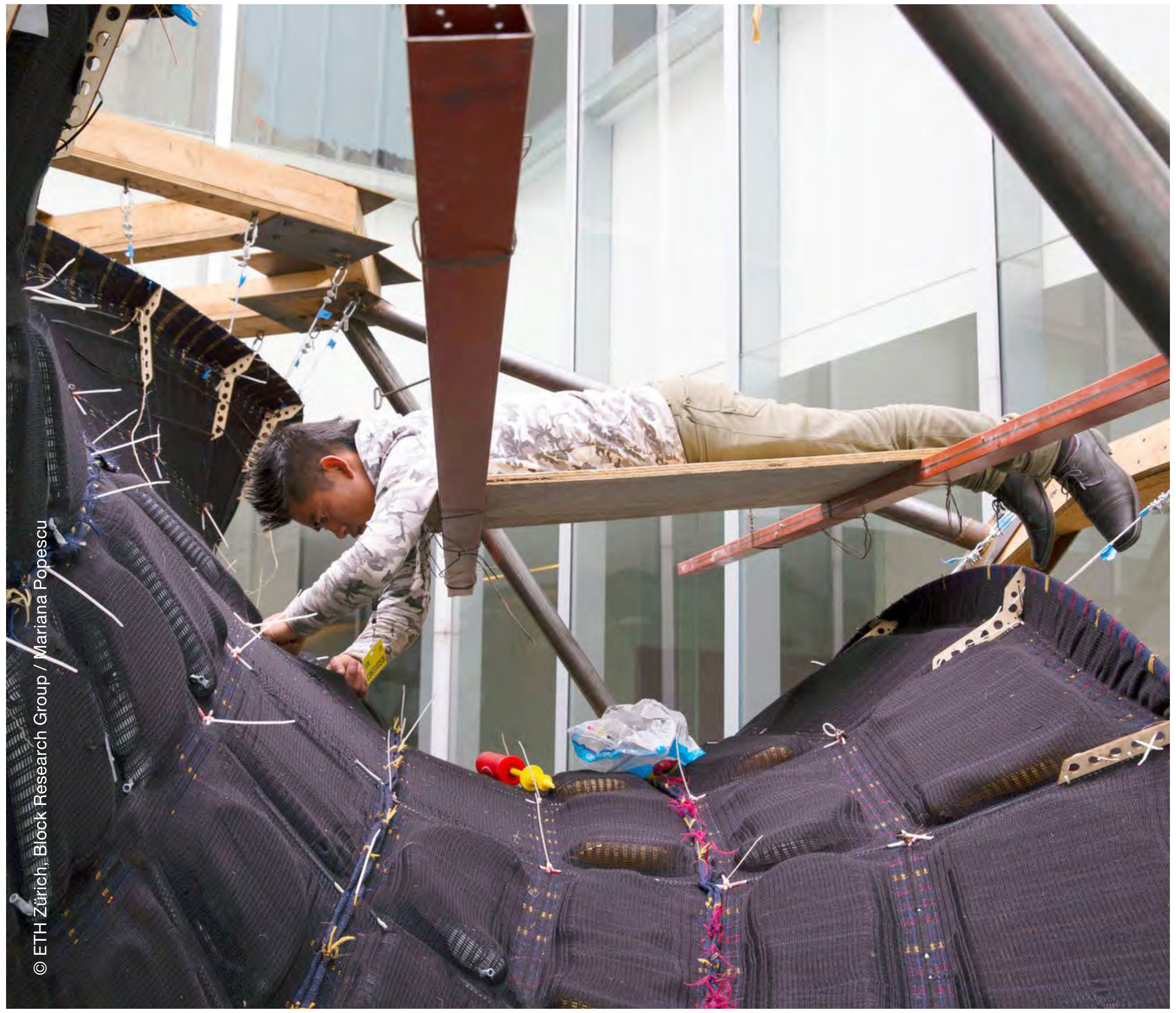
An example of 3D printing formwork is SmartSlab, a process invented at ETH Zurich. It's fabricated with 3D-printed formwork in components, assembled on site and joined with post-tensioning cables. The slab material is a series of ribs and thin shell domes achieving a staggering 70% reduction in weight compared to a standard slab. In addition, it can integrate additional functions in the slab such as building technology, lighting and acoustics treatment. SmartSlab is at an advanced readiness level (MRL7), now in operation in the DFAB HOUSE at the NEST building in Dübendorf, Switzerland.

3D printing by extrusion is dependent on the mix and flow of material in the science of rheology. There is a trade-off between speed and compensating for the hydrostatic pressure that deforms concrete. In addition to the precise control of the print head, the concrete mix and accelerators can also be digitally controlled to provide specific mix on-demand. The printer head is generally controlled by a scripted robotic arm, but when it contains sensors and cameras that "watch" what is printed, it can generate feedback in real-time to the robotic arm to change, for example, the extrusion

3D PRINTED FORMWORK
Recyclable formwork for SmartSlab developed at ETH Zurich to form complex concrete slabs of ribs and thin shell domes. (See also page 59.)

3D PRINTING BY EXTRUSION
A 3D printed house for the 2018 Milan Design Week using Cybe's extruding mobile platform.

POWDER BED 3D PRINTING
A line of closely spaced jets are moved across a powder bed to selectively bind sand with an inorganic seawater and magnesium-based binder in this printing process by D-Shape in Pisa (2006).



KNITTED FORMWORK
The KnitCandela pavilion under construction showing knitted formwork with pockets for tension cables and air balloons.

speed. This places it at Fabrication Autonomy Level 3 –initial autonomy. The print head can be controlled by an industrial robotic arm with enough reach, or by a frame larger than the printed part. On especially large jobs, a robotic arm can be mounted onto a mobile robotics platform.

One example of 3D printing by extrusion is the 3D printed house for the 2018 Milan Design Week. It was fabricated with a mobile platform by Cybe Construction and a special concrete mix developed by ItalCementi and designed by CLS Architects with Arup.

The US military also printed barracks in just two days on-site with a frame larger than the printed part. The interesting undulating design of the walls used for this demonstration project at initial readiness levels was developed with SOM Architects in 2018.

3D printing by selective bonding of material involves a frame larger than the geometrical form that is printed, for example the 6 metres x 6 metres x 6 metres of the D-Shape printer in Pisa, Italy. Like an ink-jet printer with many nozzles (300 in the case of D-Shape), it selectively deposits bonding liquid onto a thin layer of sand and repeats the operation layer by layer until the part is completed. The unbonded sand acts as support and is removed at the end of the process. The concrete parts are often printed off-site and transported to site in pieces, then assembled as false formwork for pouring traditional concrete with reinforcements.

The false formwork can also be created with a robotically welded, dense steel mesh (leaking mould) into which traditional concrete is poured. This process was invented at the National Centre of Competence in Research - Digital Fabrication by a team led by Norman Hack while he was a researcher at ETH Zurich. Called Mesh Mould, all the concrete that leaks through the mesh is levelled off by builders, exposing the accurate doubly curved complex geometry without the need for wasteful formwork. Mesh Mould is already at an advanced readiness level, in operation since the spring of 2019 in the DFAB HOUSE, at the NEST building in Dübendorf, Switzerland. As the pouring of concrete is essentially traditional, not layer by layer, the process has a high level of acceptance.

Another type of false formwork technique involves knitting, in a process invented by a team led by Mariana Popescu at ETH Zurich called KnitCrete (see also page 60). Having formulated a set of instructions in Rhino that resemble a pixel plan, a CNC knitting machine can print, at the same time, different behaviours onto the front and the back of fabric including pockets to reinforce the structure and logistical elements to advance functionality. A thin layer of concrete is added using traditional manual techniques, not layer by layer, therefore giving the process a high level of acceptance. The advantages of KnitCrete are that false formwork remains in place, visible and can be knitted with bespoke patterns and colours, that it's very lightweight, and it can be transported easily.

KnitCrete is at an early readiness level, with the technology recently scaled into the pavilion KnitCandela exhibited at the Museo Universitario Arte Contemporáneo in Mexico City, 2018 (see also page 77). A tribute to the celebrated architect and engineer Félix Candela, the design that was computationally developed by Zaha Hadid Architects computation and design research group (ZHCODE), is an expansion of the architect's concrete shell structures. In total, the project took 3.5 months from design to completion, 36 hours to knit more than two miles of yarn and weighed just 25kg in total, which could be easily transported to the site by the designers themselves.

Once on site, the double-layered textile formwork was erected using a wooden frame and tension cable-net system, made possible by integrated structural pockets that removed the need for scaffolding (see opposite). Inflatable balloons implanted into pre-knitted compartments sculpted out the desired shape, which was then coated in a thin layer of concrete to strengthen the mould. Using local labourers and traditional techniques, the concrete was added by hand, combining traditional craftsmanship and construction methods with digital fabrication techniques.

2.1.2 ADDITIVE METAL

Metal additive manufacturing (or 3D printing) has three main categories of techniques: 3D printing of moulds for casting, selective bonding or selective laser sintering (SLS), and an extrusion technique called wire arc additive manufacturing (WAAM). Most of the examples, unless specified, are at Fabrication Autonomy Level 2 – partial automation.

3D printing of moulds for sand casting involves 3D printing of a positive or negative of the part. Voxeljet of Germany printed a negative in sand followed by traditional pouring of liquid metal and breaking of the mould to reveal the complex geometry part, in a so-called "lost mould process." Alternatively, the lost mould process can use 3D printing of the positive with fused deposition modelling of ABS plastic or wax which is then placed in sand and burned to create the negative. A classic example of this technique are bespoke "spiders" that hold a glass façade. Casting is a traditional process and is fully accepted by the industry.

Alternatively, SLS is the most commonly used technique to directly produce metal parts without a mould, and this technique is referred to as direct metal. A thin layer of metal powder is laid on a platform and a CNC low-power laser traverses the bed and selectively melts the powder together. The un-bonded powder acts as support. A variation of the process, invented at MIT to avoid the use of lasers, selectively deposits a bonding agent that chemically bonds the metal in place. The advantage of this technique is that multiple metal powders can be laid, which produces novel metal alloys. Some parts might present significant anisotropy, with different strength capacity across and along the grain. The aerospace industry utilises this technique in non-critical parts, such as internal partitions, to reduce the weight of the aircraft and associated fuel consumption.

Two Arup projects used topological optimisation and direct metal printing, one for a study of Christmas lighting tensegrity structure connections and another for the metal connections of a large-span stadium roof study in 2014-15. In both cases, the self-weight of the structure is the dominant load-case and the connections represent the largest proportion of the self-weight. Therefore, optimising the weight of the connections instigates a virtuous cycle that results in an 80% reduction of weight.

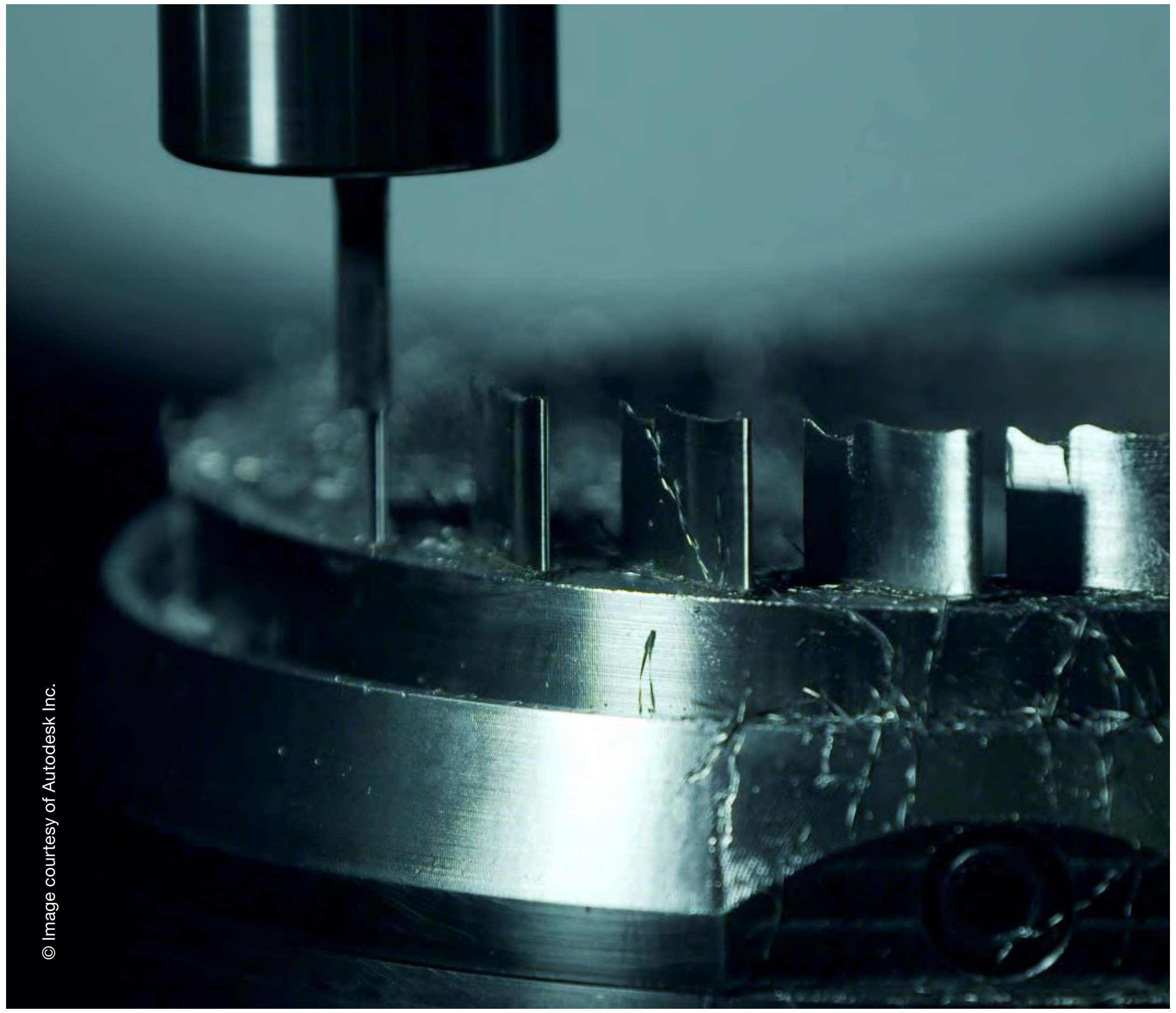
Finally, a form of metal extrusion is WAAM, a technique invented by MX3D with Dutch designer Joris Laarman (see page 22). It can be described as an automated welding process that produces a part made of welds in 3D space with no supports. The technique was first demonstrated in 2014 with the extrusion of steel to form a bench (designed by Joris Laarman Lab).

The first application in the built environment came when Joris Laarman LAB and MX3D approached Arup to apply their WAAM technique to a full-scale bridge across one of Amsterdam's canals (see page 53). This presented considerable structural design challenges of making decisions with an unknown material as well as a fabrication method that removes most traditional constraints. We discuss these challenges in section 3, Implications.

The welding process (metal inert gas or MIG) involves melting the base material and fusing a metal wire, essentially building with molten metal. This reheating process results in different material properties from the base welding wire product. To control temperature, MX3D used sensors and machine learning throughout to choose where the welding took place, which can be classified as Fabrication Autonomy Level 3 – initial autonomy.

This technique is quickly progressing through the readiness level and going into full-scale application in 2019. To compensate for the unknown material behaviour, Arup developed a material testing protocol that will continue to ensure public safety and catch early warning signs of material stress throughout the lifespan of the bridge.

ADDITIVE MANUFACTURING HYBRID WITH MACHINING
Two stages of the metal process at Autodesk Tech Centre in Birmingham, UK. This uses the Hamuel machining centre to build turbine blades on demand or improve the performance of a part after use.



2.1.3 ADDITIVE THERMOPLASTIC

Fused filament fabrication is a common 3D printing process that heats thermoplastic filament and extrudes it accurately layer by layer. The extrusion process sometimes includes two materials, a support (that is removed at the end of the printing process) and a final part material. Most of the examples we cite are at Fabrication Autonomy Level 2 – partial automation.

The printer head can be mounted onto an industrial robot for large-scale fabrication. To enable fast production at large scale with high quality, the process removes the supports, limiting the freedom of designs.

Large-scale ABS plastic printing at Ai Build, a digital fabrication start-up in London, includes a feedback loop that allows the deposition to be more adventurous and a lot quicker, and then corrects any defect in real time.

Attaching cameras to the printers and using tailored algorithms, the robots can respond to the construction process in real time, learning from any mistakes. Using ventilation cooling fans throughout printing strengthens structures in real time and enables extremely fast and responsive construction of the design with zero material waste.

Arup engineers and Ai Build developed Daedalus Pavilion, one of the largest 3D-printed pavilions in the world, measuring 5m wide x 5m deep x 4.5m high (see page 49). The pavilion was created for the Nvidia GPU Technology Conference in Amsterdam in 2016. The pavilion is made by extruding PLA (polylactic acid, a biodegradable polymer) plastics directly into space frame geometries, instead of extruding material layers.

In 2018 designer Alisa Andrasek with Ai Build and Arup engineers developed Cloud Pergola, an installation for the Croatian Pavilion and the 2018 Venice Biennale (see page 53). Ai Build is also offering 3D printing of formwork for concrete.

2.1.4 BENEFITS OF ALTERNATIVE ADDITIVE TECHNIQUES

We have described additive techniques clustered by material – concrete, metal and thermoplastics. However additive techniques can also be clustered by type across all materials with distinct advantages and disadvantages. Below is the alternative grouping:

Formwork (SmartSlab)
Benefits: uses certified materials
Pitfalls: lots of formwork waste, relatively slow, restricted geometrical freedom/complexity with minimum undercuts

Extrusions with supports
Benefits: less waste, mobile
Pitfalls: needs new continuous materials certification, restricted geometrical freedom/complexity

Powder bed (D-shape, Direct Metal)
Benefits: minimum waste, enables highest geometrical freedom/complexity, easily scalable
Pitfall: new materials need new continuous certification

Extrusions without supports (MX3D bridge, Ai Build and Cybe)
Benefits: minimum waste, mobile
Pitfalls: new materials need novel continuous certification, restricted geometrical freedom/complexity limited to a maximum of 45-degree overhangs

LARGE-SCALE 3D PRINTING
A fused filament deposition head mounted on an industrial robot at Ai Build in London.

2.2 Subtractive

A subtractive process is when material is removed by a computer-controlled tool following a "cutting path." This can be 2D in a CNC router table or 3D in a CNC milling centre or CNC band saw. Subtractive techniques have a high level of maturity with most in operation for years.

The advantages of subtractive techniques include the use of traditional stock material, the ability to create geometric complexity and the ubiquity of CNC machines.

Subtractive techniques begin with the "sculpting" of excess material, for example from a sheet of plywood or block of stone. The resulting material is natively certified, which is in contrast with additive techniques where the material needs to obtain new certification. This characteristic gives all subtractive techniques a high level of acceptance.

A subtractive technique might be limited in the geometric complexity of the part that it produces; for example, it can't create undercuts unless by rotating the part.

It's common to use a self-packing algorithm that creates a cutting pattern to minimise material waste. Equally common is the recycling of the material, for example EPS (expanded polystyrene) foam moulds; however, subtractive techniques when used to create geometrical complexity produce waste.

Most subtractive techniques are at Level 2 – partial automation, however we have found an example of Fabrication Autonomy Level 1 – augmented human in the Shaper Origin hand-held robotic router.

Shaper Origin is an award-winning router that enables precision freehand cutting by communicating with the user through a multi-touch full-colour LCD. It's described on their website as "combining computer-guided accuracy with hand-held familiarity."

Subtractive techniques are also often used for formwork with geometrical complexity, which produces a high level of waste.

2.2.1 SUBTRACTIVE FORMWORK FOR CONCRETE

There are several subtractive techniques commonly used to produce geometry-complex formwork for concrete and glass fibre reinforced concrete. These include CNC hotwire foam cutting, CNC foam milling and CNC timber routing. All these techniques produce waste. Academia is experimenting with CNC machining of other materials, including wax and even ice, which can be melted and re-frozen.

Robotic or CNC hotwire foam cutting is a relatively low-cost and fast technique that allows only ruled surfaces: surfaces generated by a straight line that sweeps freely along one or two curves in space. Multiple passes can produce more complex shapes, such as doubly ruled surfaces. Often this technique is used for rough cutting before a slower and more expensive CNC routing process is applied to generate doubly curved surfaces.

Odico Robotics of Denmark fabricated the expanded polystyrene (EPS) formwork for Kirk Kapital HQ. In the wake of achieving this breakthrough, which makes practical low-cost high-speed manufacturing of concrete formwork, Odico won more than 250 projects over the next four years becoming the first Danish robotic company held on Nasdaq in 2018.

© Shaper Tools Inc.

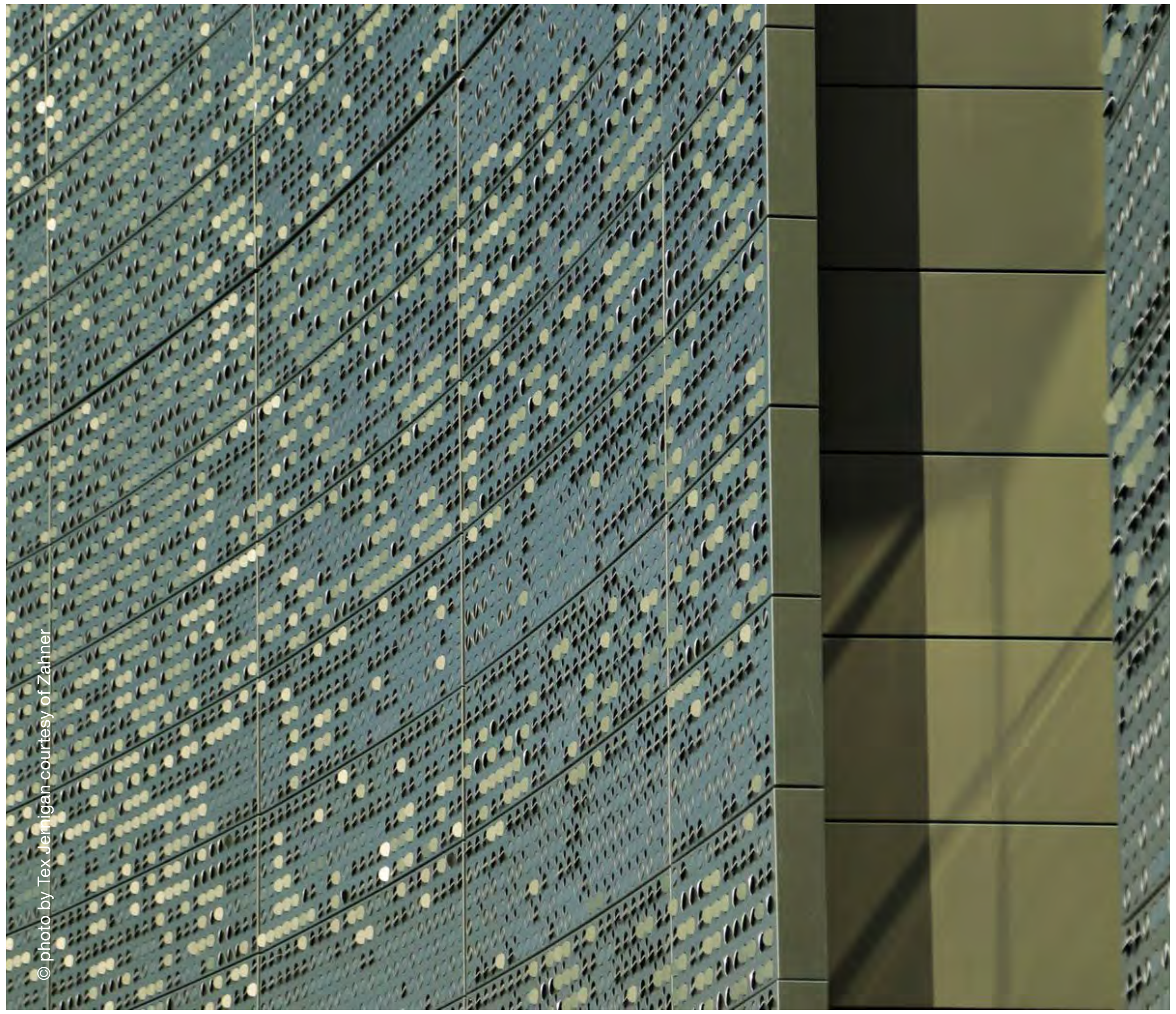
HAND-HELD ROBOTIC ROUTER
Shaper Tools, started by graduates from MIT Centre for Bits and Atoms, developed Shaper Origin, hailed as the world's first handheld CNC machine.

© Odico

HOT-BLADE FOAM CUTTING
The Danish company Odico is researching hot-blade cutting beyond the limitation of ruled surfaces to double curved ones using three robots: two flex a blade while the third advances the workpiece.

MATERIALS FOR RE-USE
Reclaimed wood wall from abandoned houses, dilapidated barns and old floors (Wanderwall Studio) as examples of non-standarised sizes.

PERFORATED METAL
Partially perforated aluminium panels create a detailed pattern of louvers and reflected light, at the Bloomberg Centre, USA.



2.2.2 SUBTRACTIVE METAL

Computer numerically controlled (CNC) subtractive techniques are common in steel fabrication. CNC plasma and high-power laser and high-pressure water jets are all used for cutting, in addition to CNC milling, depending on the cost, production rate and precision necessary.

Grant Mattis of Canadian steel fabricator Feature Walters informed designers at the Arup Explores event in Toronto that his metal shop acquired their first computer-controlled machine in 2000, and their first laser scanner in 2008. Recently they added a robotic production line to their arsenal: a fully automated steel-fitting machine from Zeman Bauelemente of Austria. All of Feature Walters' machines are capable of fabricating complex geometry, however, "the fabricator must fabricate what the designer designs," and Walters' CNC plasma cutter mostly fabricates simple standard designs.

Zahner of Minneapolis fabricated the perforated façade of The Bloomberg Centre at Cornell Tech's New York campus. A key feature of this cutting-edge, net-zero energy research facility is the louver-perforated, double-skin façade. Designed by Morphosis Architects with Arup to optimise the balance between transparency for daylighting and views, and opacity for insulation and reduced thermal bridging, the façade radically reduces the energy demands of the building. The outermost layer serves as a rain screen made up by PPG polymer-coated aluminium panels designed in collaboration with Zahner. Zahner's Louvered ZIRA (Zahner Interpretive Relational Algorithm) system was used to create the image patterning of the 337,500 two-inch circular perforations. Tabs were punched into the panelling at varying depth and rotation to control reflected light. A pixel map was fed into a repurposed welding robot, which processed the digital information into the mechanical turning-and-tilting.

2.2.3 RAW OR RE-USED MATERIALS: TIMBER AND STONE

Computer-controlled machining enables high precision and faster cutting of natural materials, and together with digital scanning techniques empowers the designer and fabricator to use non-standardised materials.

A great demonstration of this is Woodchip Barn (see page 54). This project was designed and built over a 6-month period in 2016 by the Architectural Association's Design + Make students in collaboration with Arup. Working against standardisation, the team used forked beech trees as their primary construction material, scanning each fork to create a material database. A 3D model was produced to calculate a central line that could be ordered into a truss by an evolutionary algorithm. The individual forks were then milled using robotic fabrication into a finished component before being assembled by crane.

This project is particularly inspirational in the way that it reconsiders standardisation and natural material variation, and it is a robust example of robotics assisting sustainable construction.

Beside the use of raw, unprocessed materials, digital fabrication can also enable circular economy design principles through the re-use of non-standard building components such as the timber blocks.

2.3 Forming

Forming is a digitally controlled process that bends, stretches or otherwise manipulates an object into a desired shape. In contrast to additive and subtractive manufacturing, no material is added or removed.

Forming for automotive and aerospace often involves costly and wasteful moulds that limit both the variations and accuracy of panels. Variable moulds and no-mould techniques are overcoming the limits in variability of the parts while eliminating the waste of the mould itself.

There are forming techniques at all levels of technology readiness, from mere ideas to well established. Given that traditional forming techniques are uncertain, they are prime candidates for machine learning and feedback loops.

2.3.1 METAL FORMING

There are numerous computer-controlled metal forming techniques:

- Tried and true cold metal roll forming
- Single fabricator multi-point stretch forming
- Nascent digital fabrication techniques including augmented pipe bending and incremental sheet metal forming

Cold metal roll forming offers contractors great advantages. Terry Olynyc of PCL Agile in Canada explained that his forthcoming CNC cold metal roll forming machine will provide several advantages to production in the factory: it will allow him to remove stock of standard sections and lengths – occupying precious factory space – and slash waste by forming "on demand" to the required size.

This technique also helps remove some constraints of manual construction. For example, when PCL Agile produced over 300 bathroom pods for a hospital, there was a lengthy process to reduce the number of unique designs into a ten to fifteen families. This reduction process will become redundant.

Multi-point stretch-forming

Multi-point stretch forming is a computer-controlled technique that shapes varying geometric sheet metal panels. The technique was used with stunning results by fabricator SteelLife of South Korea for the façade of Dongdaemun Design Plaza in Seoul by Zaha Hadid Architects and the Arup façade team. The façade consisted of more than 45,000 panels in various sizes and degrees of curvature. Multi-point stretch forming created the individual curvature of each panel. The accuracy of the individual panel's shape and curvature meant that the façade was constructed rapidly and with precision. As this technique becomes more commonly available with steel fabricators, designers will be able to define complex high performance façade solutions without additional resources.

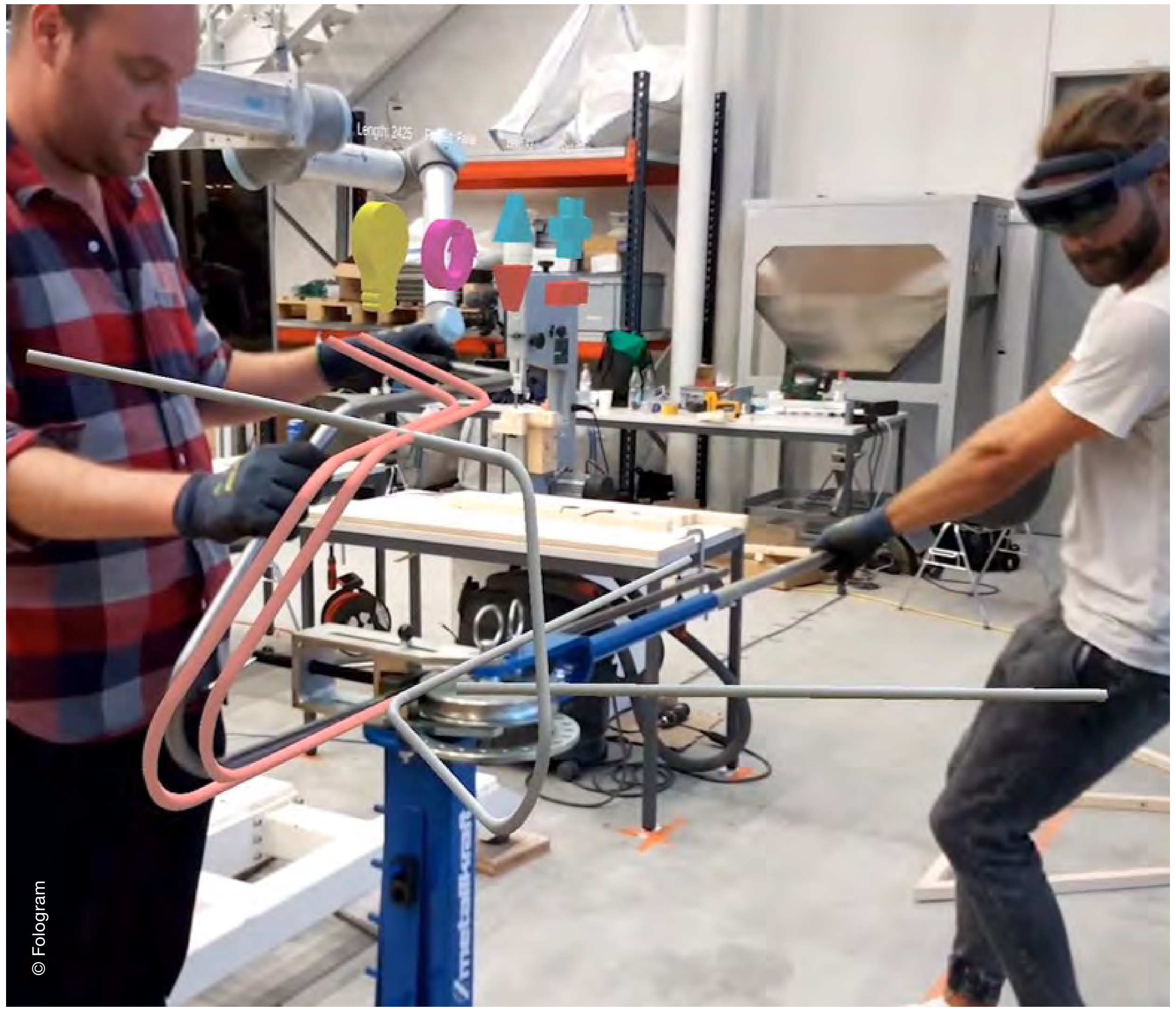
AR/VR guided metal pipe 3D bending

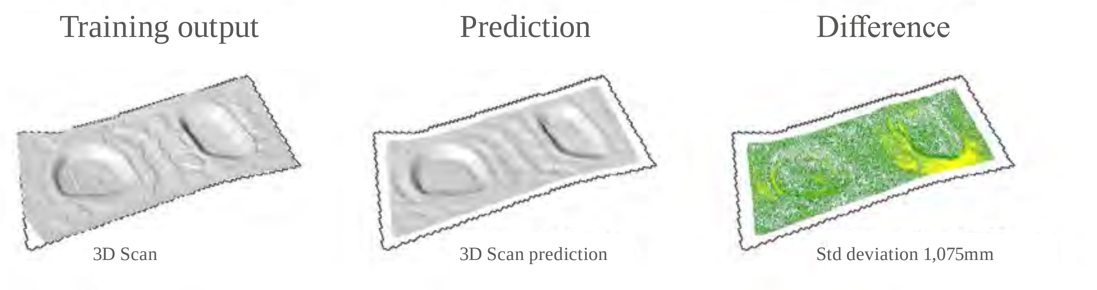
Bending pipes in three dimensions to a precise position is a complex task even for skilled workers. Melbourne-based Fologram has applied augmented reality (AR) and virtual reality (VR) to the challenge with astonishing results.

In a three day workshop at RobArch2018, un-skilled participants precisely completed a complex form sculpture, using augmented bending and assembling in half the allocated time (see page 63). The participants spent the rest of time experimenting with assembling undulating walls of standard wooden blocks precisely to their digital design (see page 5). The methodology has been applied to both found and 3D scanned non-standard objects. This technology (Fabrication Autonomy Level 1 – augmented human) has already been used by bricklayers (see cover). With the use of certified material, its impact in removing human fabrication constraints will be phenomenal.

MULTI-POINT STRETCH-FORMING
This stretch-forming equipment at SteelLife in Seoul, South Korea, has multi-point adjustable upper and lower faces which are brought together to deform the steel panel.

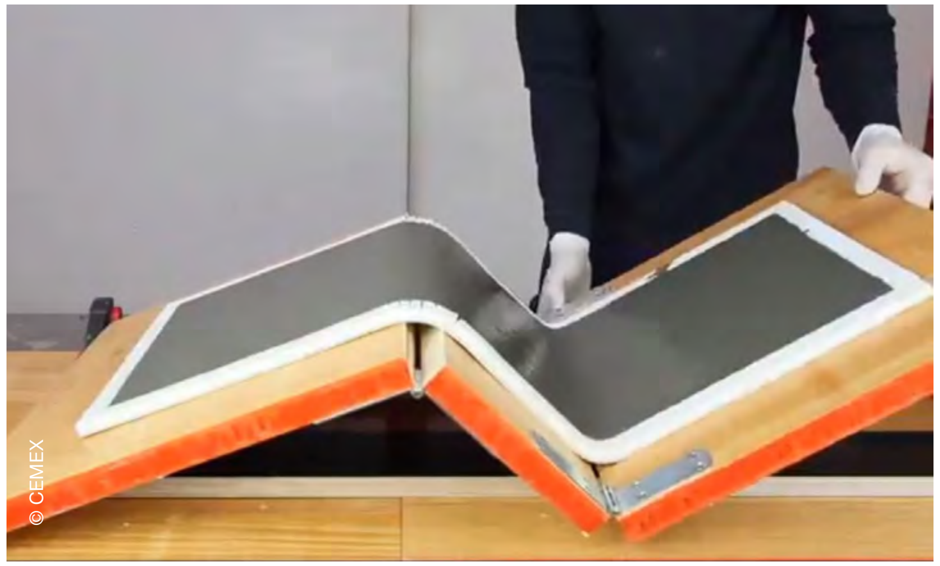
AR/VR GUIDED METAL PIPE 3D BENDING
View looking through Fologram's AR glasses where the real pipes are grey and the AR-rendered target positions are purple.





© Centre for Information Technology and Architecture (CITA), KADK

ROBOTIC INCREMENTAL SHEET METAL FORMING
From 3d scans of test outputs, CITA in Copenhagen, Denmark, are using deep neural nets to adjust fabrication information for accurate metal forming.



© CEMEX

BENDING CONCRETE
Concrete, originally formed flat, is bent in two places once viscous but still ductile, as developed at CEMEX Global R&D.

Robotic incremental sheet metal forming
As described earlier (page 24), the traditional "English wheel" technique gave complex, high-performance form to sheet metal panels without the need for a die, but it demanded highly skilled workers. The technique involved a frame holding a sheet of metal firmly in place and a round-tipped tool to deform it in small increments. Fast-forward to today: the emergent technique of robotic incremental sheet metal forming is being developed and demonstrated in universities across the world.

Despite most applications being FA Level 2 – partial automation, researchers at Centre for Information Technology and Architecture (CITA) in Copenhagen are pushing this technique to FA Level 3 – initial autonomy by using deep neural nets to predict forming tolerances. This allows them to pre-emptively adjust fabrication information to achieve the desired geometries.

2.3.2 FORMING CONCRETE

Techniques of forming or slumping molten glass into shape are widely known, but less considered are their potential use in forming concrete. Adaptable formwork, which can be reconfigured for each panel, is an interesting emerging technique that academia and manufacturing are exploring. Currently at Fabrication Autonomy Level 0 – manually fabricated, it is easy to imagine how this technique will benefit from precise robotic control.

Bending concrete
CEMEX's head of research, Davide Zampini, speaking at the Arup Explores event in Milan, explained that concrete isn't just what we see in a finished building. We don't really think about what it's like before it cures, but it has a viscous phase and the materiality is changing constantly during its fresh state. It is going through constant chemical and physical transformations, but it reaches a specific moment in curing when it can be manipulated. That is when a thin layer of concrete can be folded to create a 3D ruled shape without formwork.

Thin shell, lightweight concrete structures are very popular, but they can be difficult and costly to cast. Driven by a client request, Cemex developed a concrete mix with high ductility – lots of fibres integrated – that solved this challenge. Using the folding technique, their client was able to discard their expensive and unreliable steel formwork and create a roof element with superior performance requirements and no formwork (no waste) for a third of the cost.

Zampini believes that manipulating concrete should be carried out by robots because they are far more precise than humans. But we can't gloss over the importance of innovation in materials that make automation possible.

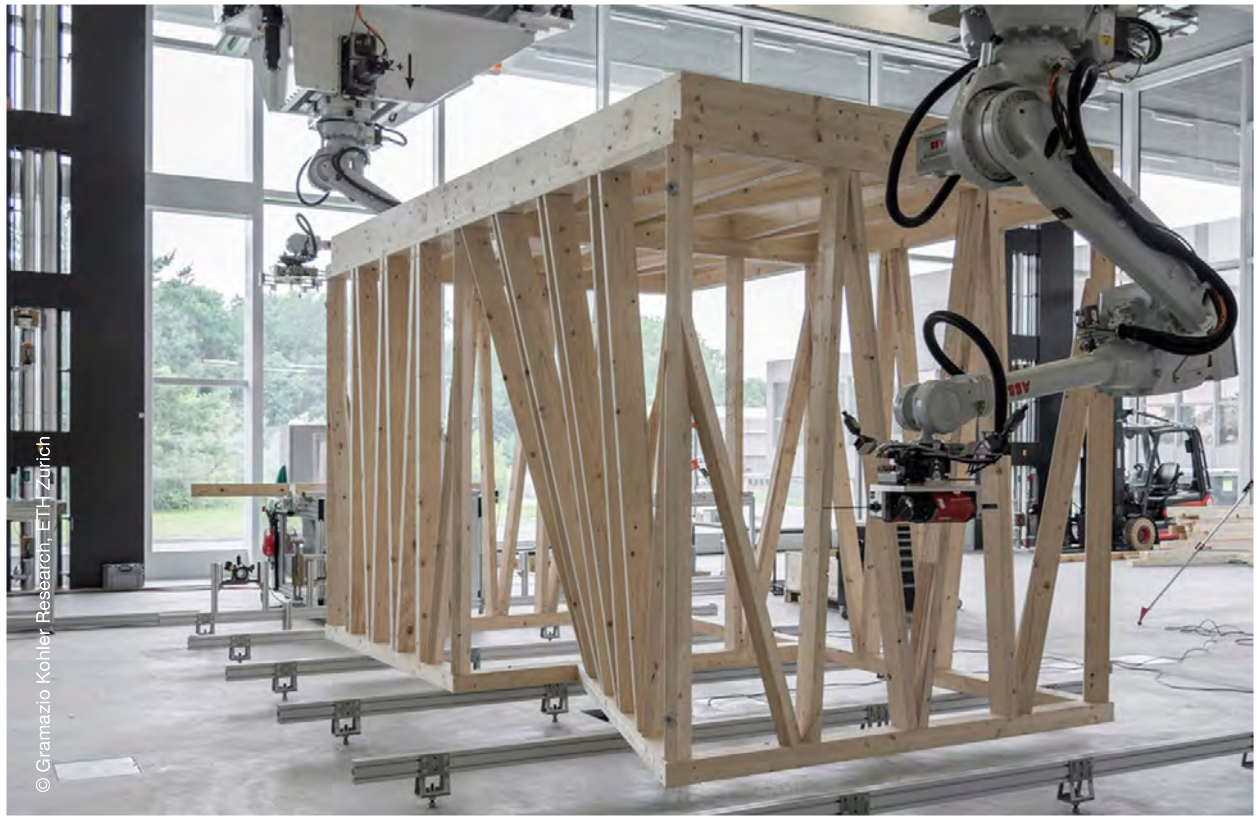
Another example of a variable ruled-surface formwork technique fabricating complex curvature in concrete panels without waste is Parametric Adjustable Mould[8] (PAM). PAM is co-invented by Swinburne Innovation Fellow Daniel Prohasky with researchers Paul Loh and David Leggett at the University of Melbourne.

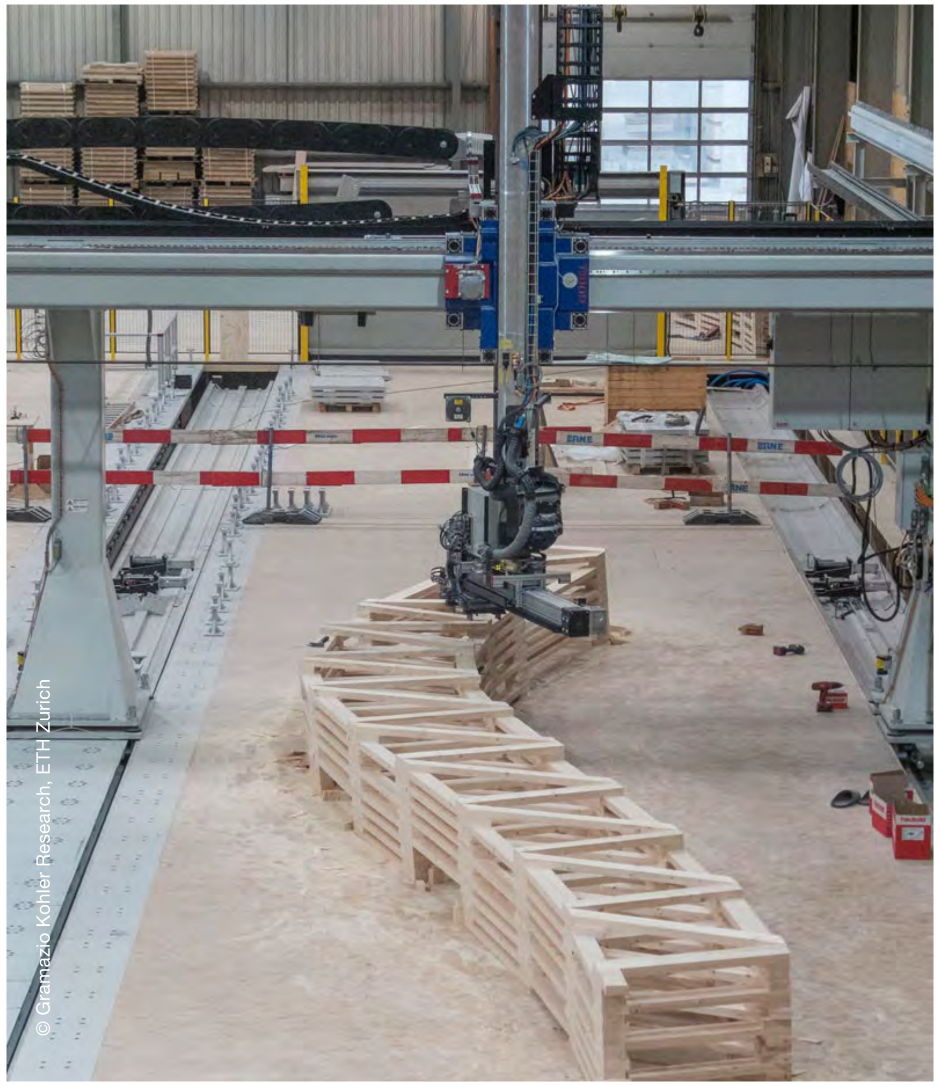
Their new company CurveCrete makes use of PAM to form a geopolymer cement made from fly-ash, an abundant by-product of coal-fired power stations currently wasted. CurveCrete geopolymer cement produces 80% less emissions than standard Portland cement, with no need to use calcine limestone, removing 55% of emissions created in cement production," explains Prohasky.

Smart Dynamic Casting
ETH Zurich's Dr. Ena Lloret-Fritschi led an interdisciplinary effort between Gramazio Kohler Research group and the Institute of Building Materials of Professor Robert which developed a novel, robotically controlled, slip forming technique they named Smart Dynamic Casting. An adjustable form, significantly smaller than the structure produced, is precisely slipped upwards to create complex geometrical form columns. The technique is limited in the forms that can be created, but it simplifies dramatically the casting of complex forms, making the added cost from a simple form negligible. Because the material is conventional and doesn't need new certification, this has a clear advantage over additive concrete techniques.

The single dynamically shaping formwork technique was used to make fifteen reinforced façade mullions for DFAB HOUSE. Each mullion was structurally optimised in accordance to the varying wind load of the façade. These were installed in the DFAB HOUSE alongside Smart Slab and Mesh Mould techniques presented earlier in this section. It has an advanced level of readiness 4-5 – technology development demonstration - operating under Swiss building codes.

SMART DYNAMIC CASTING
Continuous slip forming developed at the ETH Zurich, Switzerland, using robotic control of velocity according to the material transition from soft to hard.





SPATIAL TIMBER ASSEMBLY
Industrial robots at the ETH Zurich, Switzerland, assemble complex out-of-plane panel frames.

SEQUENTIAL ROOF
Cutting, complex assembly and photogrammetric testing of simple elements at ERNE AG Holzbau, according to a design by Gramazio Kohler Research of ETH Zurich, enables structural roof parts to be made from low-cost timber.

2.4 Robotic assembly

Robots can aid assembly processes in prefabrication as well as on site, placing bricks or lifting and moving façade elements. Static or on-track fixed-arm robots are limited by arm length and their fixed position to within metres of reach. Cable or delta robots control an end effector that can move across 10 to 100 metre cables, allowing access to more of a site where payload and precision aren't critical. The use of drones as an on-site assembly tool is currently being investigated.

Despite its current limitation in placement precision and ability to carry load, robotic assembly, with partially learned control, has great potential to enable complex form assembly that produces higher performance architectural or structural designs.

2.4.1 CABLE OR DELTA ROBOTS

The main advantage of delta and cable robots is their reach. A delta robot uses three rigid elements connected to a joint to control its position, and – as their name suggests – cable robots use cables. Whereas industrial robots are limited in their reach by the length and the strength of their "arm," cable robots provide precision positioning in much greater areas. Tecnalia of France built an indoor parallel cable robot with a footprint of 15 x 11 x 6 metres and a payload of 500kg. Cable robots can extend to a hundred metres outdoors.

2.4.2 THE SEQUENTIAL ROOF

Timber roof structural design is mostly focussed on using glue-laminated timber (glulam) with high strength and predictability. This approach can be likened to a supercar, i.e. designed to go faster and faster without a concern for resources. Using the same analogy, The Sequential roof project is more comparable to a Toyota Prius as is designed to reduce consumption.

The complex process of cutting to shape, place and join was made possible by computer control. In contrast to high-embedded-energy glulam solutions, this roof is made of young, untreated and low-embedded-energy timber inspired by the timber generally used for pallets. A computer-controlled gantry at ERNE AG Holzbau manufacturing facilities precisely cut and assembled – in a free-form complex geometry – nearly 50,000 elements, following the design by the ETH Zurich Chair of Architecture and Digital Fabrication, who eventually occupied the building. This process of placing material only where it is needed is sometimes referred to "big scale 3D-printing".

2.4.3 SPATIAL TIMBER ASSEMBLY

At the DFAB HOUSE, researchers from ETH Zurich used precise industrial robots to assemble not rationalized (standardized to one-size-fits-all worst-case) sections of timber studs into double-curved out-of-plane frames. These were subsequently clad on site with a translucent façade of aerogel-filled ETFE.

Assembling timber joists to follow a complex curvature allows for a reduction in the material necessary to achieve the same structural performance. Another interesting aspect is that assembly occurred directly in space (as opposed to assembling each wall/floor on a flat bed and then putting them together). For this, two robots are cooperating and serving as temporary supports for the structure until it is self-stable.

3 Implications

What are the implications of these digital fabrication techniques?

The digital transformation of construction re-emphasises basic design principles by freeing decision-making from the otherwise in-built constraints of traditional fabrication. This contrasts with the industry's current emphasis on designing for construction standardisation. With the digital transformation approaching, it's risky for designers to be inattentive to how fabrication is evolving as it renders their advice redundant and potentially detrimental. The designer's advice for manual construction becomes increasingly redundant in two ways. On the one hand it produces design for traditional onsite fabrication which is unsuitable for those clients that need to scale. On the other hand it produces design for off-site manufacture and assembly which doesn't perform within the constraints of one planet.

Digital fabrication techniques fundamentally imply the removal of manual fabrication constraints – such as plumb line, spirit levels, linear planks – from the design and decision-making process. In general terms, this means designers can abandon reliance on simple orthogonal geometric form, simple assemblies and simple materials. It's critical for the designer to unlearn manual fabrication constraints while learning the constraints of digital fabrication.

Digital fabrication techniques are also constantly emerging, evolving and maturing at lightning speed. Constraints also change dramatically during the evolution, from a technique's maximum built volume, material composition or simply the availability within a region. Acquiring a good knowledge of the technique is time consuming for the designer, and perhaps frustratingly, some knowledge will become redundant and potentially detrimental very quickly.

The following examples of early adopters' implications are clustered in three categories: design, business and society.

PARTIALLY AUTONOMOUS 3D PRINTING
A detail of the Daedalus Pavilion printed by Ai Build (see page 49). The partially autonomous printing process, though globally accurate, is locally inaccurate giving a character of hand knitting.

3.1 Design

Several Arup early adopters designing with digital fabrication point out the different and often multiple ways in which design and decision making is changing, from:

- Manual to data-driven design
- Standard components to bespoke design
- Geometrically simple and flat to complex and undulating or rippling
- Repetition to diversity or mass customisation
- High tolerance to precision fabrication
- Best practice recipes to first principles (seemingly counter-intuitive)

Design changes emerging from early adopters and those to come will be crucial to ensure that our decision making for our clients in the built environment is the best possible. All these changes require new learning by the designer in practice, while we wait for academia to integrate them in the curriculum.

3.1.1 DESIGNING COMPLEX FORMS

With Daedalus Pavilion for the 2016 NVIDIA Conference in Amsterdam, Ai Build designed a large walkthrough space frame solution to showcase their novel PLA plastic 3D printing technique (see opposite and page 46). Ai Build with Arup engineers abandoned discrete standard components for a continuous bespoke entirety. Naturally, the design was too complex to address manually. Enter the data-driven methods.

Daedalus Pavilion is an excellent example that continuously changes the space frame shape to reflect the loads. Decisions like these would normally increase costs and incur delays but come for free with a digital fabrication technique. This novel design required a close collaboration between the Arup structural engineer and the Ai Build makers to optimise the sections.

Sometimes it takes years from the invention of a new technique before it is adopted. This was the case of 3D printing of military barracks designed by SOM Architects with undulating perimeter walls.

Traditional military barracks are made of geometrically simple, flat, prefabricated walls that stack easily for transportation. But when the barracks are 3D printed in concrete on-site, eliminating at once the constraint of transportation and human fabrication, it was possible to undulate the walls to reduce material while increasing stability, still at no additional cost or waste from complex formwork. The process also reduced workers and time needed to assemble traditional components,

BESPOKE METAL NODES
In contrast to a conventional metal node (left), two levels of topological optimization towards a tensegrity structure with increasing removal of design constraints. By Arup, WithinLab (now Autodesk Within) and CRDM (now 3D Systems On Demand).

SPACE FRAME FROM BESPOKE ELEMENTS
The Daedalus Pavilion is a 3D printed, thermoplastic space frame printed by Ai Build (see also page 46). The design consists of section elements which change continuously according to the loads, enabling dramatic savings in material and formwork.

UNDULATING PERIMETER WALLS
3D printing of concrete on site for walls of US military barracks. The design by SOM Architects is undulating to reduce material use while maintaining structural performance.

BESPOKE STORM WATER COLLECTOR
3D printing off-site enabled this concrete structure to fit exactly with the existing pipes (from 3D scanning), which minimised installation time and disruption.

which is a good thing when constructing in a dangerous war zone. An interesting challenge would be posed should a need for disassembly and reuse arise.

Structural performance isn't the sole driver for increased complexity. Small variations in the instructions of the computer-controlled fabrication can be used by the architect to soften a façade, to create a subtle branding or to personalise design. In the façade of the SF MOMA extension by Snøhetta Architects, Arup and Kreysler & Associates as fabricators, the architect designed a ripple effect to convey a sense of "silky elegance". In the case of the roof cladding for the LA Rams stadium designed by HKS architects with Zahner of Kansas City as fabricator, the pattern generated by the tens of thousands of uniquely sized and positioned ventilation holes subtly branded the building when viewed from planes landing at LAX and didn't impact the time or cost of the panels.

Indeed, the personalisation or mass customisation available with digital fabrication, following more than a century of standardisation, demands a sea-change in how designers think. High levels of personalisation are now possible at minimal or no additional cost and time.

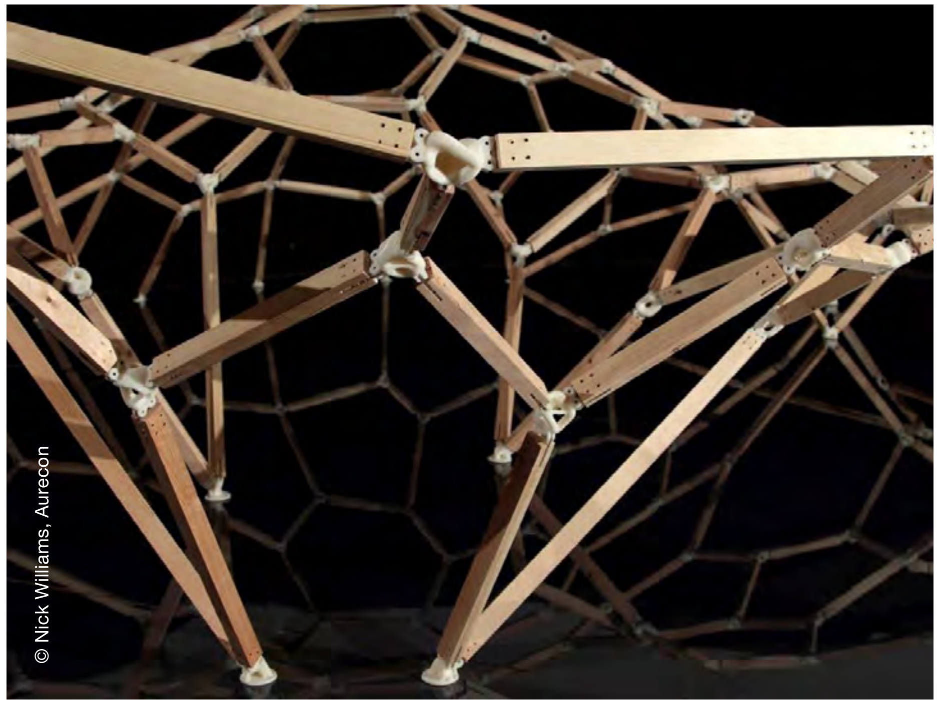
3.1.2 DESIGNING FOR MASS CUSTOMISATION

Whereas personalisation is thriving in fashion and products, the design of a bespoke storm water collector provides a rare example that can inspire many other applications driven by the client's desire for minimum disruption and service continuity of critical infrastructure.

When the Société Auxiliaire des Distributions d'Eaux embarked on the retrofit of a storm water collector in the city of Lille in 2017, they needed to ensure business continuity. The retrofit involved a road closure. The designers considered two techniques: laser scanning and 3D printing by France's XtreeE with Point.P Traveaux Publique, a French leader in construction materials distribution. Fitting standard-designed collectors on site to existing drainpipes all at different angles would have created delays. They chose instead to make a bespoke concrete collector 3D printed directly from 3D scans of the existing drainpipe positions. This saved installation time on site and minimised road closures.

Another application of mass customisation where the architectural node optimisation induced a virtuous cycle of material savings happened in The Hague.

DESIGNING FOR MASS CUSTOMISATION
For this space frame of the Engineers Australia Convention Pavilion (Melbourne, 2014), bespoke nodes were customised for the differing load cases and angles at every point.



Here, the Arup research project was to re-design an architectural node of the tensegrity structure for Christmas lighting at the Grote Marktstraat. In a tensegrity structure, connections account for a large portion of the weight. By substantially reducing the connection's weight during the first cycle of topological optimisation of the design – without compromising its functionality – a virtuous cycle of weight reduction was instigated.

The resulting complex form design, bespoke to its location, used a selective laser metal sintering (SLMS) additive manufacturing technique, enabling bespoke designs at no additional cost.

When the thinking was re-applied in the second version of the node design, going back to first principles and taking advantage of the unlearning of further legacy manual fabrication constraints, a further reduction of weight was achieved. This reduced the material by an impressive 80% without compromising the node functionality. The additive process meant there was no additional waste. More information about the collaborations needed to deliver this project can be found in section 4.

Node optimisation can also induce a virtuous cycle of material savings in large stadium roofs. An Arup research project by James O'Donnell to re-design architectural nodes using the bespoke load cases of the Singapore Sports Hub achieved similar results.

3.1.3 DESIGNING FROM FIRST PRINCIPLES

Concluding that designing with digital fabrication requires only new data-driven design is incorrect. As explained for the tensegrity structure node, first principle design allowed further material reduction to be achieved.

In a similar way, the design development of the MX3D bridge across a canal in Amsterdam had stalled; counter-intuitively it was the first principle approach of a bridge domain specialist proposing an inherently structural U-channel shape that enabled the team to unravel the design challenge.

Instructed by the stresses, the team applied structural optimisation techniques to redistribute material exactly where it was needed. The resulting design met the needs and criteria of all invested parties, including the artist's aspiration to demonstrate the ability of the novel WAAM technique to print a complex form (see page 30).

Not all material properties of the material produced by WAAM are fully known. Making structural decisions without knowing the material behaviour meant that the team conducted many tests, and the artefact will be constantly monitored live. With an interest in the project, Imperial College London recreated a complex ABAQUS finite element structural analysis model that enabled the team to verify its own results.

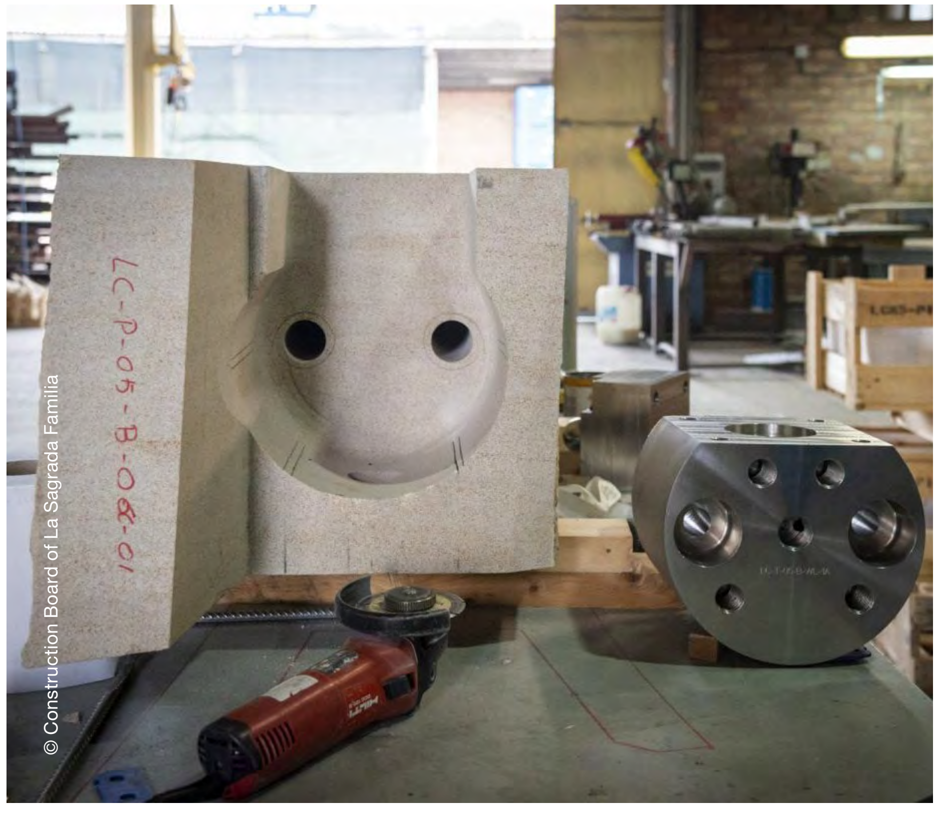
HIGHLY EFFICIENT DESIGN
3D printed US military barracks with undulating concrete walls by SOM

© MX3D

DESIGNING FROM FIRST PRINCIPLES
Digital fabrication of this bridge by MX3D freed the design from the constraints of manual fabrication, instead enabling it to respond to structural engineering requirements from first principles. (Dutch Design Week, 2018, Eindhoven)

© James Griffith/Arup

AIMING FOR MAXIMUM FORM COMPLEXITY
The Cloud Pergola designed by architect Alisa Andrasek was 3D printed by Ai Build for the Croatian Pavilion at Venice Biennale in 2018. Arup's structural design of the strong, lightweight form followed from first principles of resolving the forces, voxel by voxel.



DESIGNING WITH PRECISION TOLERANCES
End face of a stone panel alongside a stainless steel anchor for the Sagrada Familia, Barcelona. Post-tensioning cables in the stone require precising drilling of the holes and fabrication of the anchor to avoid stress concentration from imperfections.

DESIGNING WITH NATURAL MATERIALS
The primary arching structure of the Wood Chip Barn is made of non-standard beech forks, as sourced directly from the Dorset forest. Digital design and machining of the complex joints enabled the inherent natural structural capacity of the forks to be exploited for the roof loads.

3.1.4 DESIGNING WITH PRECISE TOLERANCES

One last fundamental implication of digital fabrication is the change from design with high tolerance to precision fabrication. Digital transformation shifts the moving early of “appropriate design” from human skills to machine capabilities, therefore making it independent of cultures and geographies.

In the case of the Sagrada Familia project, precision construction is how one can describe the robotic cutting and drilling of stone, two techniques that enabled the design team to think of post-tensioned stone with stainless-steel cables inside the stone.

Post-tensioning is a technique commonly used in concrete, where the casing for the cables is laid by workers before casting the concrete. However, with Sagrada Familia, the cable casings are precisely drilled in the blocks of stone. Cable fittings and pockets in the stone are precisely machined to improve the adherence and increase the strength of the “composite.” This kind of stone composite design solution can only occur with the precision of digital control

3.2 Business

Precise computer control of fabrication and construction not only has implications for the design as seen in the previous section, but also has disruptive implications for business. Companies adopting digital fabrication early are experiencing unprecedented business growth. At the same time, ignorance of digital fabrication can make a company's design services redundant.

3.2.1 MANAGING CONSTRUCTION UNCERTAINTY

Emerging investments in digital monitoring of the construction site provide the contractor with much better understanding of their business and less waste. One example is Gammon Construction of Hong Kong using a "digital twin" of the construction site, continuously tracking equipment, materials, progress and workers on site. This gives them an edge over the competition, especially on projects like airport expansions where construction occurs alongside a busy operation.

From a client and designer point of view, precise control of construction might require less planning ahead, a quicker start on site, and counter-intuitively, allow for more uncertainty and late changes in the design and decision making without added economic risk or delay or at least consciousness of the changes. Think of the changes that a TomTom GPS instigates in the planning of your journeys. The ability of predicting quickly and precisely the consequence of a potential late change, which can too often create chaos if not managed, could represent a unique selling point for the design firm that first takes advantage of the "digital twin" of the construction site.

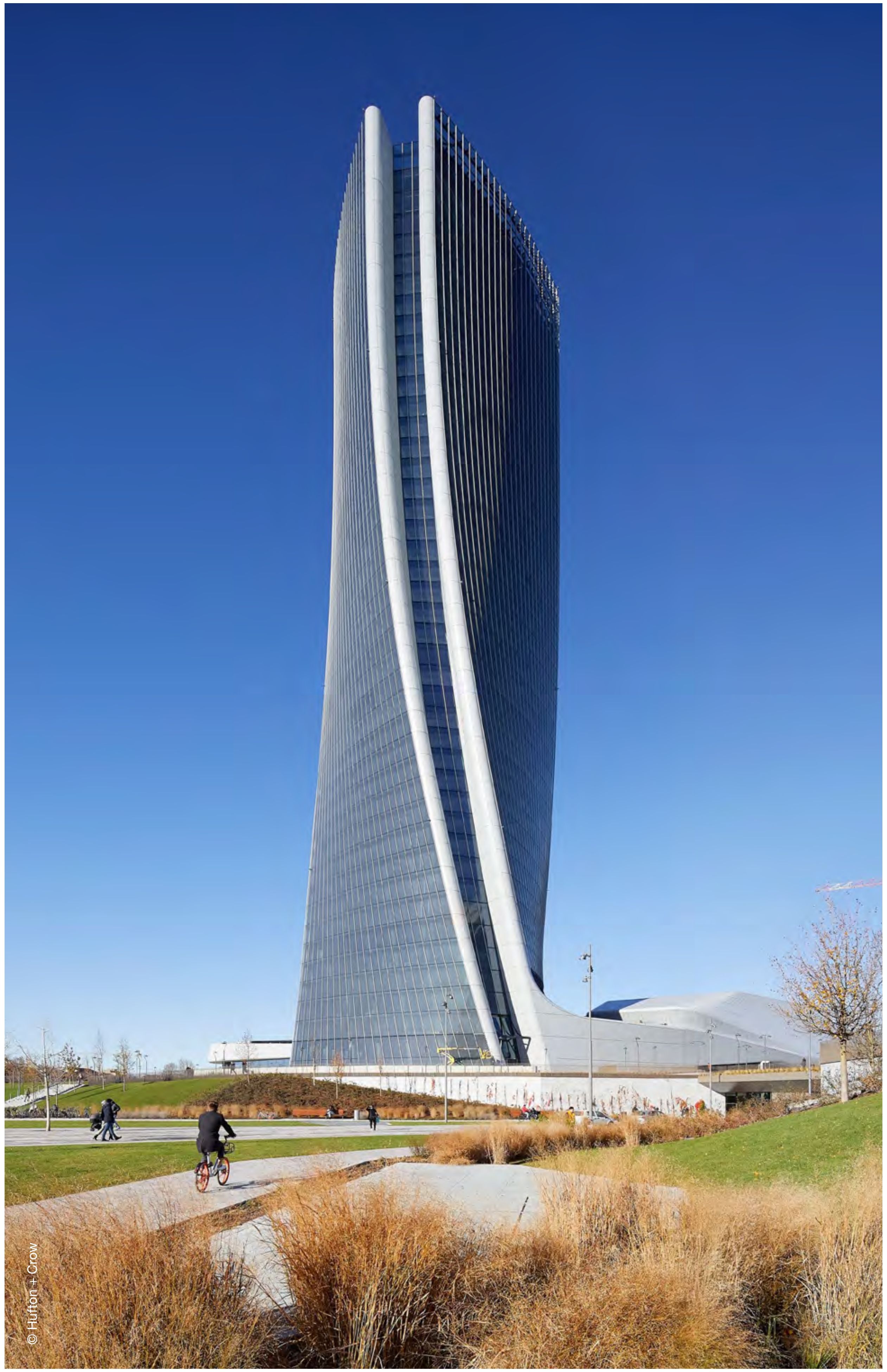
3.2.2 WINNING THE IMPROBABLE

Another example is when Zaha Hadid Architects invited the industry to tender for the construction of their new Generali Tower in Milan. The bid was eventually won by Cooperativa Muratori e Braccianti (CMB), a long established Italian contractor. CMB's Director of Design Arnoldo Tegon, speaking at the Arup Explores event in Milan, explains that CMB had invested heavily in BIM and digitisation of construction in the years leading to the bid for the tower, and allegedly the contractor's advancement in their digital transformation was a key factor in winning the project. The delivery of Generali Tower, designed for digital fabrication, was still a steep learning curve. However, the project propelled CMB to win a €300m hospital in Denmark, a considerably larger contract in a market that would have been previously improbable for CMB.

3.2.3 MAKING SERVICES REDUNDANT

Precision construction at Sagrada Familia shows the impacts to our traditional business model (see pages 25, 54 and 59). When Arup was invited to advise on the completion of the cathedral, the proposal was to complete the very tall and slender towers using standard steel sections and then clad with stone. This solution, however, added too much weight to the existing foundations. Arup's solution, designed with precision construction, used a composite steel and stone light enough for the existing foundation. This decision made the standard steel section's engineer design and construction redundant. Digital fabrication made the impossible possible.

It's difficult to predict the speed at which some of these novel techniques will penetrate the industry and it is depended from many factors. Most businesses look at the slow progress of the past to predict the future. We would make the case for moving early: to avoid being left behind as adoption by others accelerates and avoid the reputational risk of appearing to be designers with increasingly out-dated techniques. Finally, there is an opportunity to attract talented staff before the entire industry does.



DIGITISATION OF CONSTRUCTION
The Generali Torre in Milan designed by Zaha Hadid Architects with Arup Façade Engineering is a construction with large-scale complex geometry. The contractor, CMB, were early adopters of digital construction in Italy, which was key to winning this project.

3.3 Society (UN SDGs)

As one of the industries that produce the most waste and carbon emissions globally, construction has a responsibility to reduce its environmental impact. In recognition of this, 175 countries and an increasing number of global businesses including Arup have signed up to the UN Sustainability Development Goals.

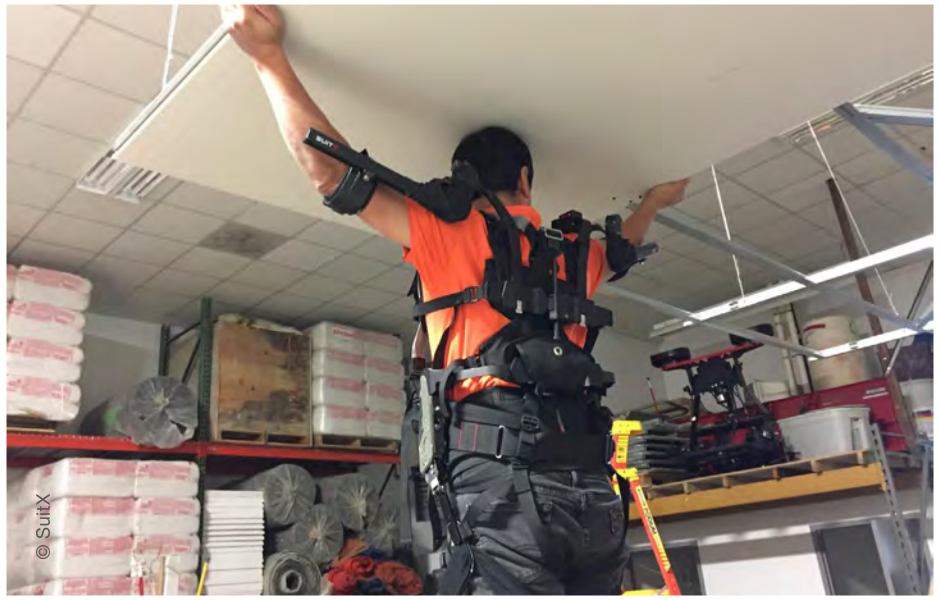
For thousands of years, the complexity and diversity of construction forms have enabled generations to create extraordinary structures, from the minarets of the Arab world to the churches of the western world. The industrial revolution, with its emphasis of standardisation and repetition to scale the production of the built environment, lost that ability. Digital fabrication however enables complexity and diversity of form, and perhaps also resilience, without compromising the ability to create at scale.

Whereas the traditional approach to automation in construction aims at removing workers from the construction process, digital fabrication aims to augment human skills with the precision of computer control. One example is the Fologram forming techniques where instructions to the worker occur via a head-mounted VR/AR display (see cover and pages 4 and 39). Another is the exoskeletons used to support a worker in complex and heavy tasks.

Digital fabrication enables the effective use of unprocessed materials – for example the tree trunks of the Woodchip Barn project (see page 54) – and the reuse of non-standard salvaged components – for example timber blocks (see page 36) – directly addressing the increasing scarcity of virgin materials.

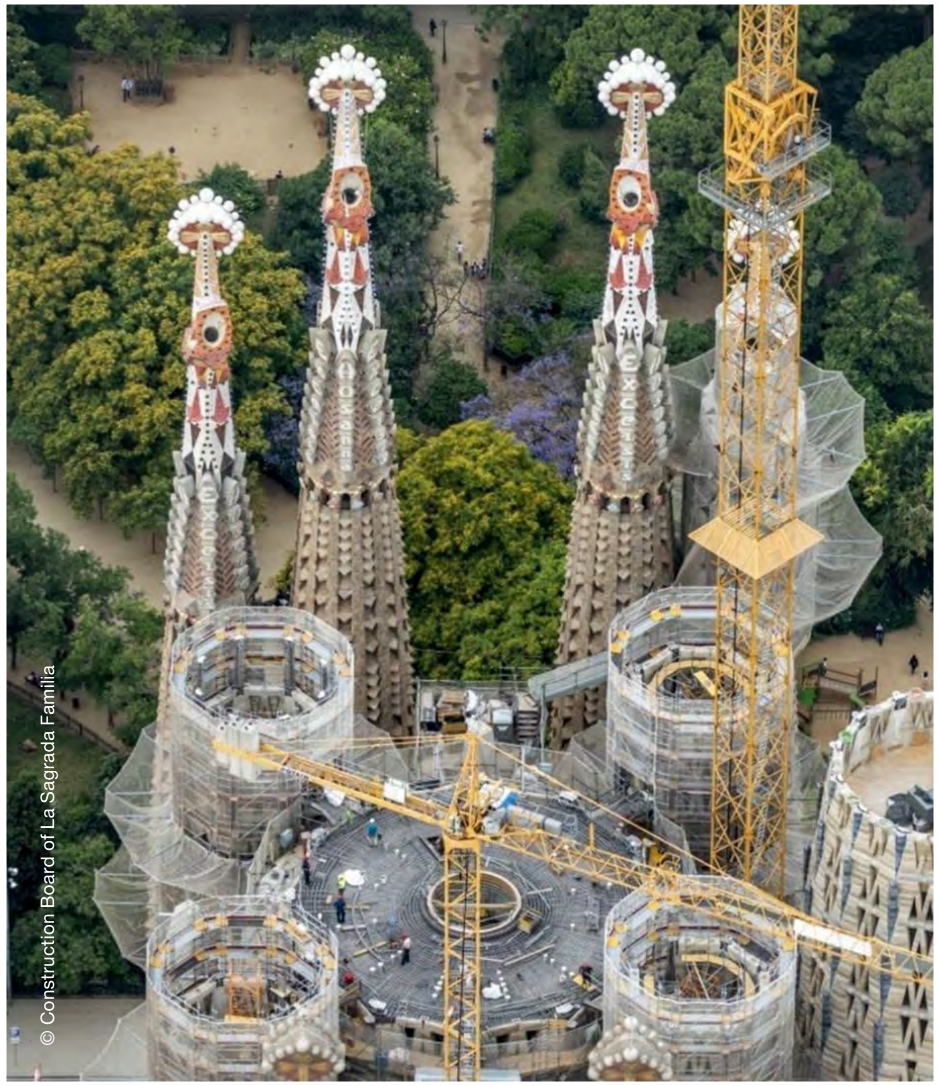
Several of the projects presented, from SmartSlab (see also page 27) and KnitCrete at ETH Zurich (see pages 28 and 74) to the architectural node for the Christmas lighting developed by Arup (see page 52), achieved staggering savings of three quarters of the materials without incurring any waste. As these techniques evolve from research to broad applications, the cost will decrease and the impact on society will be huge.

Another type of impact is cultural. It took 100 years to construct 60% of the Sagrada Familia in Barcelona. The current solution designed with digital fabrication that emerged when traditional construction ran out of options, is on track to complete 40% in less than 10 years by 2026, the centenary of the death of its architect Antoni Gaudí. This is an accelerated pace of ten times an order of magnitude. Arguably society would not have this completed church if it wasn't for digital fabrication.



AUGMENTING HUMAN SKILLS
This worker exoskeleton by SuitX reduces risk of injuries and could augment worker precision and ability to conduct complex tasks.

MATERIALS SAVINGS
Installation of SmartSlab at DFAB HOUSE in Dübendorf, Switzerland. Manufacturing these slabs from 3D printed formwork (see page 27) enabled a staggering three quarters saving of material.



BUILDING THE UNFEASIBLE
By 2018, six central towers of the Sagrada Familia in Barcelona, Spain, were remaining to be built. Their planned completion in 2026 has been made feasible through digital fabrication.

© Pieter Bleghs

4 Actions

Now, what are actions of early adopters of digital fabrication?

In every region and market, designers and decision makers must first assess digital fabrication's relevance to their clients' aspirations and its uptake by the industry. For example, construction cost in India is heavily influenced by material costs, while scarcity of skilled workers dominates costs in Switzerland.

For each new project, practitioners should also evaluate what fabrication autonomy level is most appropriate: from digitalising a simple fabrication task to fully digitalising the entire fabrication, assembly and construction process. In Japan the implementation of digital fabrication has a pronounced "social" focus to keep the "human in the loop", which might restrict the application to simpler options.

Finally, digital fabrication techniques evolve quickly compared to the speed of changes in construction. Designers must pay continual attention to the industry and its developments. Honest time horizons for projects must also be considered.

REDUCING FORMWORK WASTE
The complex high-performance structural geometry of this arch by Block Research Group at ETH Zurich is the first application of KnitCrete, which has minimal formwork waste.

4.1 Observe

First, observe designers who are using or considering digital fabrication and then reflect on the potential implications these techniques could have on your designs for novel client challenges – think reducing materials and waste. The following list shows where to look.

4.1.1 CONFERENCES

Designing with Digital Fabrication is now a cornerstone topic at architecture and design conferences in academia and industry.

4.1.2 DESKTOP STUDIES

Watching conference talks or reading their proceedings is also an efficient way to learn the language and culture of digital fabrication.

- FABRICATE 2011, 2014, 2017, and 2020.
  Proceedings are free to download from UCL Press
  https://www.uclpress.co.uk/collections/built-environment/
- Robots in Architecture Vimeo channel
  A collection of over 176 videos of different digital fabrication techniques.
  https://vimeo.com/robotsinarchitecture/videos/
- 2nd DIGITAL CONFERENCE 2020. Proceedings, talk recordings and Cement and Concrete Research Journal special issue are free to download.
  https://digitalconcrete2020.com/

4.1.3 LEARNING JOURNEYS

Learning journeys provide the opportunity not only to learn from the experience of the doers, but also to learn about new techniques and implications to design and business, speaking directly with innovators and discussing applications to specific projects and client challenges.

In February 2019, a group of 18 architects and designers from the Arup Architectural Skills Network of Europe visited the Robotics Fabrication Lab at ETH Zurich and the digital fabrication demonstration DFAB HOUSE at EMPA in Dübendorf.

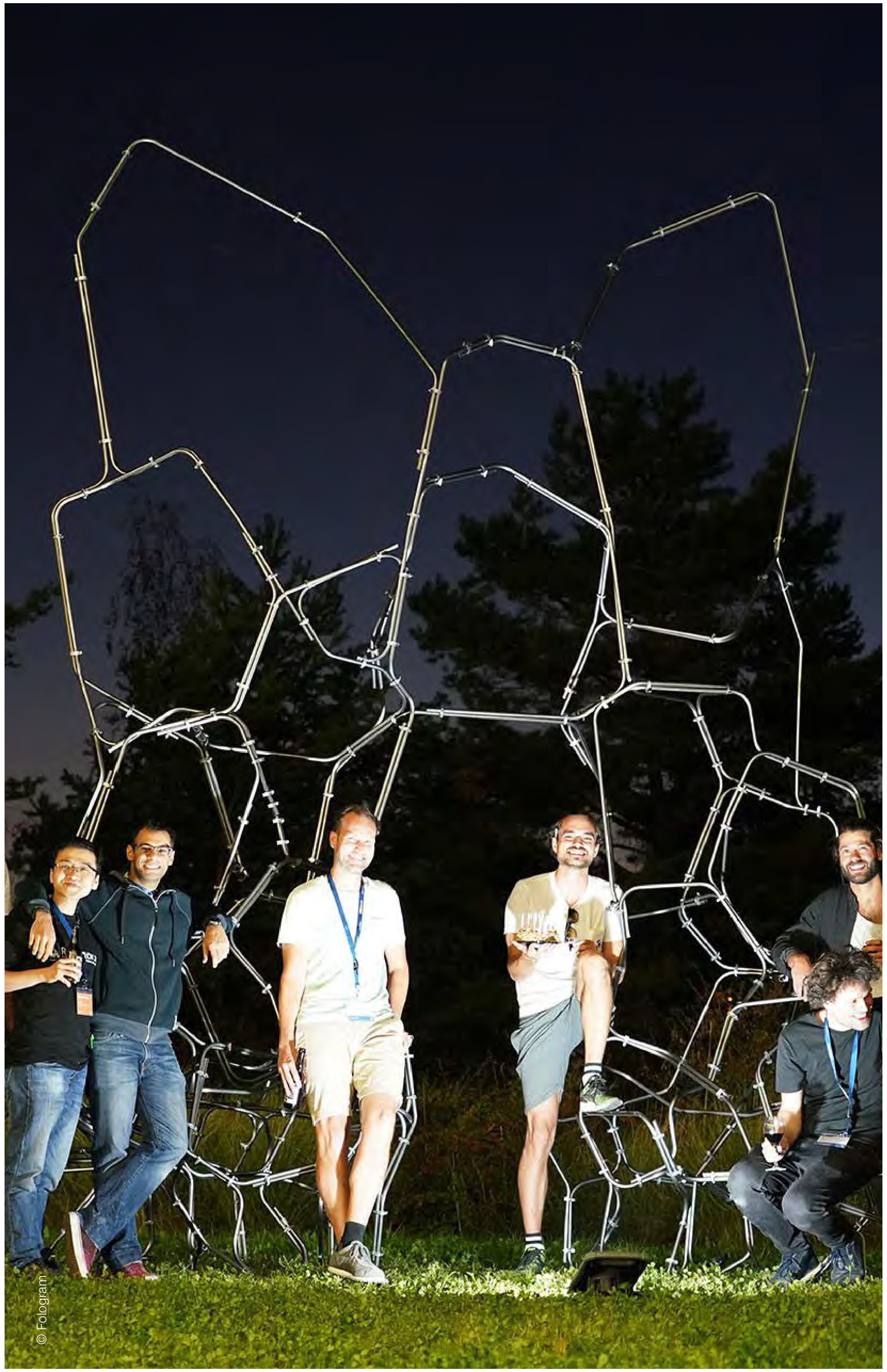
At the end of the day, the participants were given the opportunity to share as a group their reflections, facilitated by four questions:

1. What new metrics of success are/will your clients be using?
2. What digital fabrication techniques might be relevant to new metrics of success?
3. How will relevant digital fabrication techniques impact your advice/design?
4. What are the success stories about learning the language and culture of digital fabrication, and what you are going to learn?

James Finestone, Arup's Europe Architecture Leader and Director, reflected "It was a very interesting and inspiring event and more eye opening than I had imagined. […] The most basic (and banal) metric over time will be staying in business – staying relevant. The most interesting progress will continue to support our creative differentiation – becoming leaders in this new space. Are we doing old things in new ways? Are we going to find ourselves doing completely new things in completely new ways?"

4.1.4 OTHER LEARNING JOURNEYS IN 2018:

- Autodesk Tech Centre in San Francisco at Pier 9 and Robotics Lab
- Bmade at Bartlett School of Architecture, UCL, Here East, London
- Autodesk Tech Centre in Boston's Seaport at Built Space
- Autodesk Tech Centre in Birmingham
- Laing O'Rourke Explore Park in Worksop
- HK Productivity Centre in Hong Kong



UNSKILLED COMPLEX FORMING AND ASSEMBLY
Proud practitioners celebrate a fun and rewarding experience of digital fabrication over three days. They formed and assembled the complex sculpture of a metal pipes assisted by Fologram's augmented reality goggles at the RobArch workshop in Zurich in 2018.

4.2 Engage

Early adopters have most successfully expanded their awareness and understanding in design with digital fabrication by engaging with specialist partners. In this section we explore success stories of colleagues adopting the language and culture of digital fabrication.

4.2.1 SPONSORING AN EMBEDDED PHD

As early as 2005, Arup Melbourne principal Peter Bowtell sponsored designer Dr. Paul Nicholas, an embedded PhD candidate from RMIT's SIAL lab directed by digital design "rock star" Professor Mark Burry. Unusually, the embedded PhD sat in the sponsor's office. The three of them supported artist Nadim Karam in the fabrication of The Travellers, an early example of digitally fabricated permanent installation on the Sandridge Bridge in Melbourne.

The PhD supervision gave Bowtell an early introduction to the culture and the language of digital fabrication, one he applied to the radical design innovation demonstrated in at least two of Bowtell's outstanding projects in Singapore of Marina Bay Sands and Sports Hub.

4.2.2 ENGAGING WITH THE INNOVATION ECOSYSTEM

In Europe, the team in Italy successfully partnered with CLS Architects in Milan and Berry Hendriks, founder of CyBe Construction, a Dutch start-up, to deliver the "first 3D printed house in Europe" for the Milan Design Week in the spring of 2018. The project received much attention both from visitors and the media. This partnership enabled the design team to quickly establish themselves as thought leaders in the field in Europe and the industry.

In the UK, Chris Carroll, Henry Unterreiner and James Griffiths have successfully partnered over the past few years with Daghan Cam, co-founder of London based start-up Ai Build, to provide structural design for the Daedalus Pavilion at the NVIDIA conference in Amsterdam in 2016, and more recently for Cloud Pergola designed by Alisa Andrasek for the Croatian Pavilion and the 2018 Venice Biennale.

James Griffiths has taken his understanding of designing with digital fabrication further and published a paper for the Advanced Building Skins conference in Bern, Switzerland in October 2018 on "Automated Over-cladding for City-Wide Retrofit" with façade engineer Todd Grice and former Arup Director and now Chair of the Welsh Government Advisory Group on the Decarbonisation of Existing Homes, Chris Jofeh. The paper argues a for potential step change in the speed of retrofitting enabled by bespoke digitally fabricated components.

4.2.3 AMSTERDAM PARTNERING SUCCESS STORY

Probably the best-known digital fabrication project by Arup is the topologically optimised steel node described in section 3 (page 48). In 2013, Salomé Galjaard and the team in Arup Amsterdam successfully partnered with Dr. Siavash Mahdavi, founder of Within Lab in London (now Autodesk Within) and metal 3D printing shop CRDM (now 3D Systems) in High Wycombe, UK, to re-design an architectural node of the Christmas lighting tensegrity structure (see pages 51-52).

This is a model story for engaging with the innovation ecosystem. With a background in Industrial Design Engineering and specialisation in Interaction Design, Galjaard was able to partner for the creation of this highly influential project in the role of the integrator, without specific skills in software programming or additive manufacturing.

This project received massive attention from media worldwide, instigated much discussion and projected Galjaard into thought leadership in the field. Since then, Galjaard has continued partnering with Digital Fabrication experts in the Netherlands and worldwide including Hedwig Heinsman, co-founder of promising Dutch start-up Aectual and DUS architects, developing excellent understanding.

Galjaard's thought leadership has raised Arup's profile in this field in general, and for the Amsterdam office in particular. This higher profile and the confidence in the office gained with the node experience was key when, a couple of years later, the office received a call from Tim Geurtjens, CTO and Gijs van der Velden, COO at MX3D, looking for a structural design partner for their invention.

PARTNERING WITH SMES
For architectural nodes of the tensegrity structure for the Christmas lighting at the Grote Markstraat, Arup partnered with WithinLab (now Autodesk Within) and CRDM (now 3S SYSTEMS) for their design and fabrication.

EMBEDDING A PHD CANDIDATE
The Travellers are sculptures on Sandridge Bridge in Melbourne (2005). Their design is a result of collaboration by the artist with a PhD candidate, their professor and an Arup practitioner.

ENGAGING WITH STUDENTS
Sawmill Shelter is a roof canopy form at the AA School facilities in Hooke Park, Devon. Its design and fabrication in 2018 shows the benefit from Arup practitioners engaging with faculty and students.

Joris Laarman designer and MX3D had until then successfully completed designs for chairs with Wire Arc Additive Manufacturing (WAAM), a novel digital fabrication technique (see page 30), and were looking at scaling up its application, to the size of a pedestrian bridge.

Amsterdam Arup Director Mathew Vola led the challenge for Arup and the team to design and make structural decisions with an unknown material and process. In the autumn of 2018, the completed bridge was exhibited at Dutch Design Awards 2018 while waiting for its prime spot on an Amsterdam canal, and was given the prestigious Public Award.

2020 will see the 12-metre stainless steel bridge installed across one of the oldest and most famous canals in the centre of Amsterdam, the Oudezijds Achterburgwal. The original design team for the bridge has now considerably enlarged to achieve a “smarter bridge”. A digital twin of the bridge has been constructed that is informed by this unknown material testing and by data from the real bridge with the support of Lloyd’s Register Foundation, Alan Turing Institute and Imperial College London. This is a brilliant story of learning and success in designing with digital fabrication that could be replicated across all engineering teams.

4.2.4 SPONSORING A ROBOTICIST PHD

Duncan White, Arup Director and Science and Industry Business Leader, has an unusual perspective and interest in learning the language and the culture of digital fabrication and robotics.

White is working with clients that construct robotic facilities in distribution centres and manufacturing, and is sponsoring Julius Sustarevas, a PhD candidate in Robotics at UCL in London. Sustarevas’s PhD is focussing on the communication and interaction of multiple diverse robots on the construction site. The insights emerging from this industrial supervision enable White to understand where the field is going and what might be the consequences for the design of the robotic facilities; for example, robotics facilities are traditionally planned in a very rigid, gridded fashion, whereas robots’ increasing ability to communicate will loosen the restrictions of planning. White has used the EPSRC’s CASE Award programme that is available to colleagues in the UK.

4.2.5 ENGAGING WITH STUDENTS

A desire to develop an understanding of designing with digital fabrication as well as trust in the techniques lead Arup Associate Director Francis Archer, Vincenzo Reale and their colleagues in Arup Building Engineering London team to collaborate with students at the AA School’s award-winning Hooke Park facilities in Devon, UK.

Archer collaborated on milestone project Wood Chip Barn in 2016 (see page 54) and Reale collaborated on the Sawmill Shelter in 2018 (see page 66).

Using small-section timber in tension configured with anticlastic curvature to resist snow and wind load, Sawmill Shelter is an innovative solution taking advantage of the precision of digital fabrication. It won the Innovative Timber University Research category at the TTJ Awards.

Beside developing understanding, collaborating with the students offers the opportunity to attract digital fabrication talent to the industry. Former Arup architect, and Bartlett School of Architecture, UCL graduate, Gary Edwards supervised students of the 2018 March Design for Manufacture programme at his alma mater, which also houses The Bartlett Manufacturing and Design Exchange (Bmade). MArch Design for Manufacture graduate Cristina Garza joined the Arup architecture team.

Other offices benefitted by engaging with academia in this field. The Melbourne office has research collaborations with Swinburne University, RMIT and Melbourne University where former Arup Director Brendan McNiven is now Enterprise Professor in Architectural Engineering with a special interest in digital fabrication.

Toyo Ito’s National Taichung Theatre, an award-winning doubly curved concrete shell plate solution, benefitted from structural leadership of Senior Associate Mitsuhiro Kanada out of Arup’s Tokyo office. The project won the Institute of Structural Engineering 2017 award for construction integration. Specifically, the jury wrote: “Awarded for projects demonstrating excellence in the interaction between the structural design and the construction scheme where this represents a significant feature of the structural solution.” To develop the confidence and experience necessary for such innovative structural decisions, Kanada also holds a position at Tokyo University of the Arts.

4.3 Practice

Practicing design with digital fabrication is the most successful way to understand it. Rapidly evolving digital fabrication techniques might force more designers to make this commitment. Arup offices in Sydney, London, Amsterdam and Toronto are planning or have implemented maker spaces in their redesign.

4.3.1 PRACTICING AS A HOBBY

Practicing designing with digital fabrication doesn't need to be major time commitment. With a passion for fabric screen-printing, Arup Associate Director Sophie La Bourva used a laser cutter to transfer her designs onto screens. Her experimentation with this digital fabrication technique gave her understanding and confidence for her engineering designs and decisions in her role as principal designer with Zaha Hadid Architects on the Dongdaemun Design Plaza in Seoul. This design employed multi-point stretch forming (see pages 38-39).

4.3.2 CREATING DEMONSTRATORS

Designers Jenessa Man, Daniel Park and Geoffrey Iwasa of Arup Toronto wanted to "really engage with the act of making and fabrication itself." The team created a provocative installation for the Arup Explores event in Toronto to beautifully demonstrate how digital fabrication doesn't necessarily involve industrial robots replacing the human. Their augmented reality application enhanced the human with the precision necessary to construct a cantilever of blocks inspired by the V&A Dundee.

Counter-intuitively, in this instance, the human provided the force and the machine added the necessary precision. Demonstrators like this develop understanding and promote the image of being at the cutting edge of innovation.

4.3.3 REGISTERING FOR A PHD

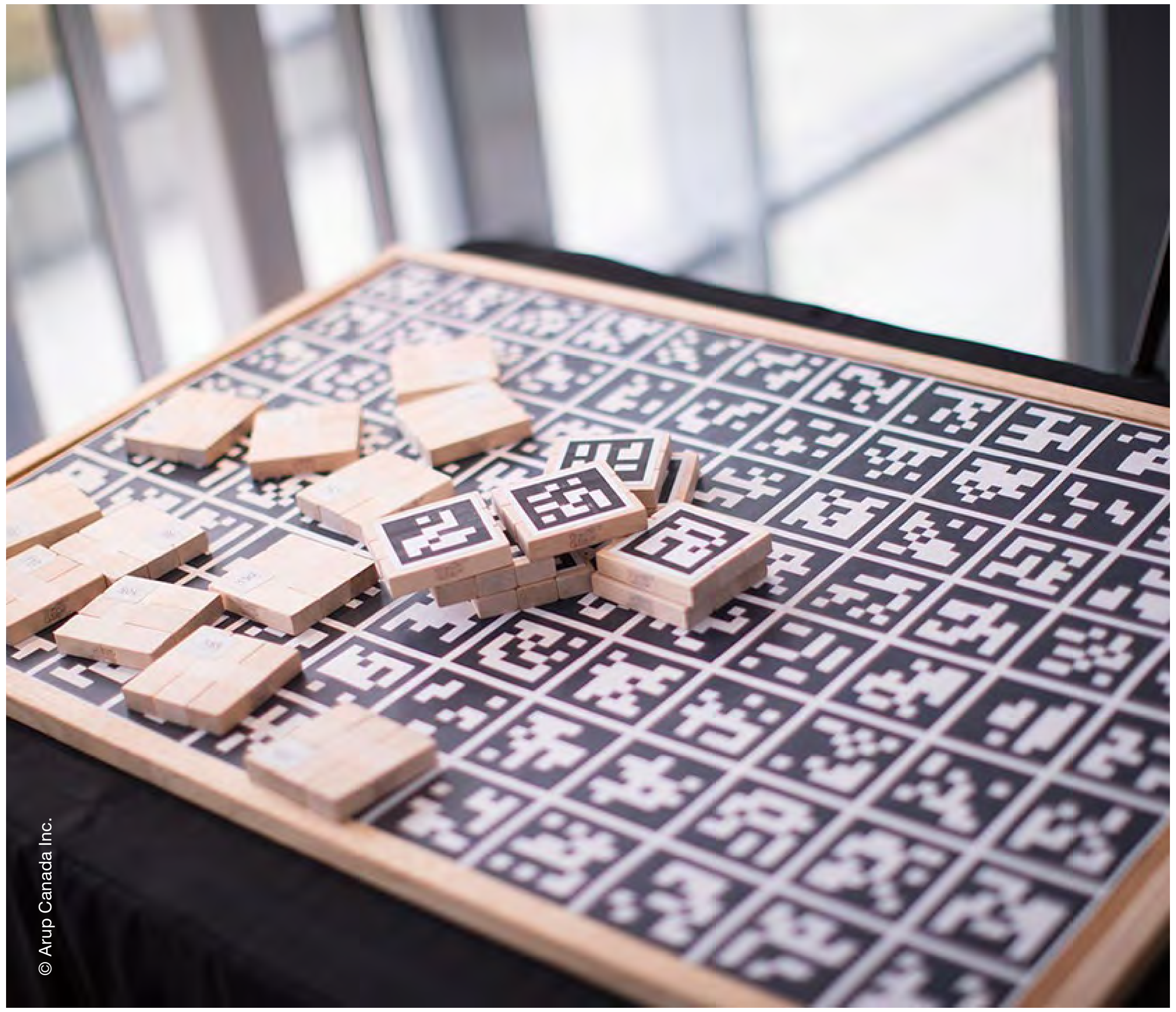
As a busy Senior Associate at Zaha Hadid Architects in London and co-founder of CODE, the firm's COmputation and DEsign research group, Shajay Bhooshan registered for a PhD in the Block Research Group at ETH Zurich as well as a studio master at Architectural Association Master's programme.

The tri-perspectives from inventing, teaching and practicing gave Bhooshan a uniquely robust opportunity to take full advantage of digital fabrication. Famous for their fluid NURBS surfaces design solutions, under the influence of Bhooshan, the Zaha Hadid Architects practice is using the new constraints to improve its downstream constructability, but also to express the unique beauty in rational constraints. In 2018-19 Bhooshan also started to teach on the Bartlett's long-standing MSc Architectural Computation programme, which is now joined by a PhD stream in the same field.

As more architects follow Bhooshan in embracing designing with digital fabrication, structural engineers, such as Arup, are required to move beyond traditional decision-making recipes and to embrace data-driven design.

PRACTICING AND REGISTERING FOR A PHD
This exploration of 3D concrete printing in non-horizontal layers is by Shajay Bhooshan, co-founder of ZHA CODE and PhD candidate at Block Research Group, ETH Zurich, Switzerland.

CREATING DEMONSTRATORS
The base and blocks of the Arup installation are marked by QR code to enable a laptop visualization to guide unskilled delegates in the complex assembly.



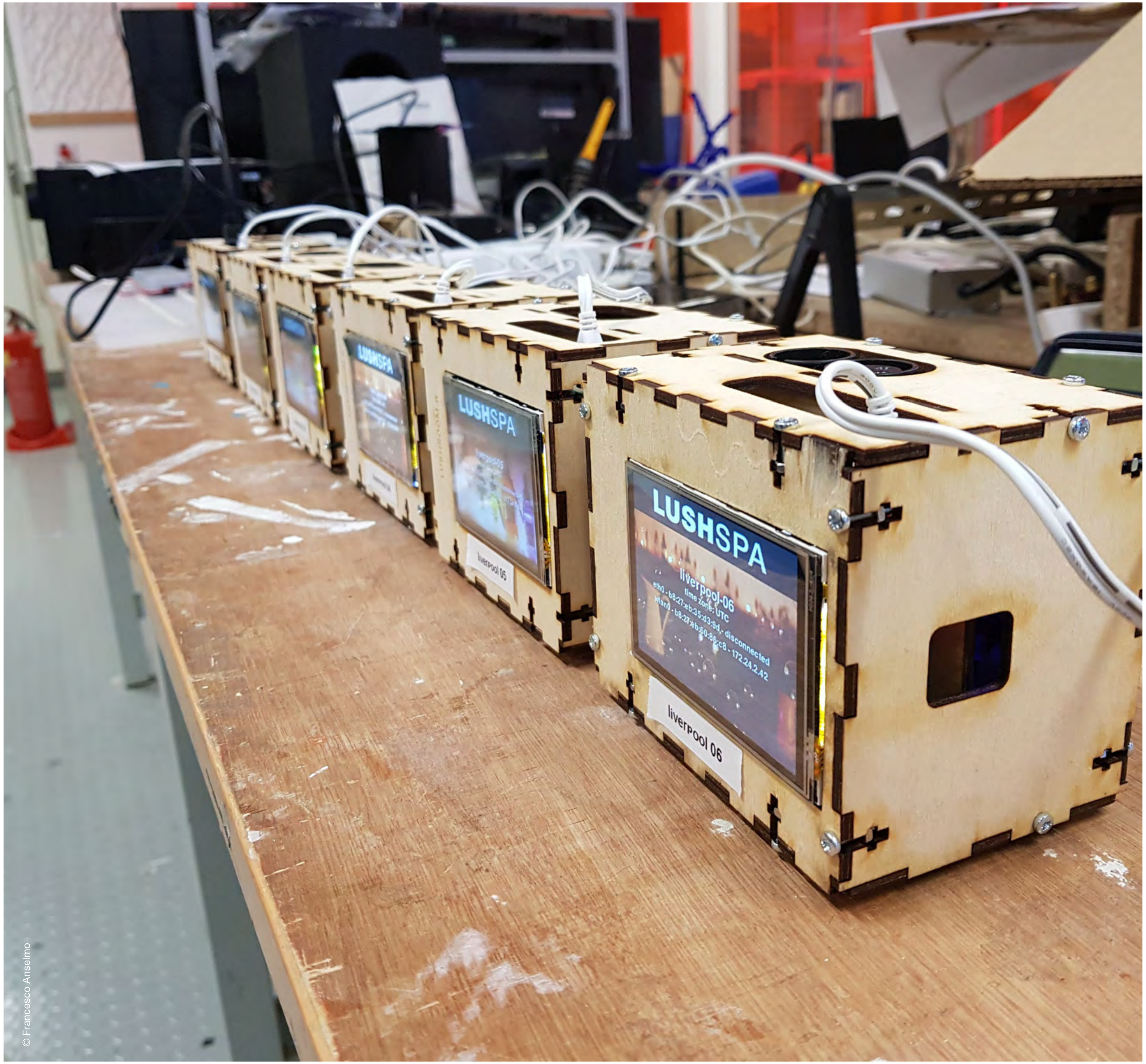
4.3.4 FABRICATING REVOLUTIONARY IOT SOLUTIONS

Francesco Anselmo, Associate Director in Arup in London, is passionate about light and interaction's influence on people's wellbeing and the experience of architecture.

Anselmo has designed with digital fabrication all along. His bespoke solutions range from lighting and IoT casings to IoT desks. Unusually, he has fabricated his small batch productions with computer-controlled equipment, for example laser cutters, sometimes assembled with the help of his students and colleagues.

However, Anselmo's pioneering design and decision making doesn't stop at designing with digital fabrication in mind, but exploits the opportunities offered by the digital control of the built environment in mind too, taking solutions to higher levels of performance. His recent design for a cloud-based audio and light media player for sensory treatment rooms is described by the clients, Lush and Michael Grubb Studio, as a "revolutionary lighting scheme for the Spa".

Lastly, designing with digital operation is the theme of our next Arup Explores global programme which is completing our trilogy on the future of design: designing with data, with digital fabrication and with digital operations. Watch this space!



© Francesco Anselmo

FABRICATING REVOLUTIONARY IOT SOLUTIONS
Bespoke IoT solutions fabricated for a client in Arup London's Maker Space and ready to ship.

5 Programme methodology

The Arup Explores programme is designed to gain the maximum diversity of inputs – in this case, provided by multiple digital fabrication techniques – and of verifications from a diverse group of building and infrastructure designers from all regions. In short, the Arup Explores program takes full advantage of Arup's global presence and multiple design practices.

We interviewed more than twenty global and regional skills leaders within architecture, structural, building envelope, materials and digital networks as well as Arup's expert designers with digital fabrication, and we listened carefully to their implications. We conducted desktop research and participated with Arup experts in conferences in Stuttgart, Zurich and Boston, and organised learning journeys to centres of excellence. We worked with the five regional Foresight teams and business champions to organise six Explores events with six to ten expert speakers each and fifty to sixty designers, clients and contractors to help us reflect on the consequences for design, business and society, and learn from early adopters' successful strategies to keep pace with change.

Finally, we have presented and discussed consequences for designers and the industry at large with offices in Brisbane, Hong Kong, Melbourne, Milan, Singapore, Sydney, Toronto and Tokyo.

Drafts of this briefing note have been circulated to digital and design leaders, as well as experts inside and outside the firm, and their comments are incorporated in this version.

EXPLORING WITH STUDENTS
This bridge demonstrator was digitally designed according to raw materials available by the students of Mitsuhiro Kanada, Arup Senior Associate and Associate Professor at Tokyo University of the Arts.

Postscript

CHRIS LUEBKEMAN
Arup Fellow and Director
Global Foresight, Research and Innovation

I cannot count the number of times that I have walked down a street and stopped to peer through the hoarding into a construction site. I can't help it. The hustle and bustle are always alluring. It is incredible that all of those pieces, which start off being dug out of the ground someplace or dimensioned in a mill or forged in a factory of some description, seem to end up in the right place, at the right time and in the right position.

Design and construction are both tight (or not so tight), and amazingly choreographed chaotic processes. There is always a direction and an intent. It doesn't matter to me if what I am looking at is a vertical or horizontal object. It doesn't matter if it is large or small. Each time I renew my wonder of our collective professions. We shape. We craft. We connect. We mould. We carry an awesome responsibility to make the places and spaces for humanity to not just survive, but to thrive.

When I stand there, I also wonder what was going thru the mind of the design team as they pondered the myriad of possibilities. What constraints did they consider were important? Which did they discount? What helped them make those decisions? Who made them? Which factors were in the background that they did not even know were influencing them? Did they think about how this 'thing' was going to be built? Did they try something different this time around? Or did they do what they knew would work?

What will these same construction sites look like twenty years from now? I wonder what I would see if I look through that future hole in the hoarding. I wonder what the construction site will sound like. I wonder what those workers will be doing with their hands. I wonder what tools they will be using. I wonder what materials I would recognise and which would baffle me. I wonder what machines will be there. Will there be fields of cranes? Legions of robots? Robo-copters dropping things in place? Will I hear jack-hammers and see welders? Will there be any waste at all?

I think about the implications of this excellent report. How fast will the different methods which have been described be commonly adopted? Where will we see rapid adaptation? Where will we see no transition? What impact will these new techniques have upon our already suffering planetary systems? Will they help or hinder the housing of the needy? Will they usher in, or delay, a carbon neutral economy? Will these methods increase the velocity of the achievement of the Sustainable Development Goals? Will greed or good win the day?

Digital Fabrication was adopted by some industries long ago. It has been flirting with the construction sector for a long time. And now we see evidence that it has begun to be adopted in some parts of the world. This report shows some of the best examples of leading-edge research and project implementation. I have found it to be inspiring food for thought. I wonder how it can help us create a legacy which we can, and will, be very proud of.

I wonder how digital fabrication will help us be the best ancestors that we can be.

MATERIALS SAVINGS
The KnitCandela Pavilion at Museo Universitario Arte Contemporáneo in Mexico City, 2018, designed by Zaha Hadid Architects and ETH Zurich, demonstrates use of the KnitCrete false-mould technique.

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ABOUT ARUP

Arup is the creative force at the heart of many of the world's most prominent projects in the built environment and across industry. We offer a broad range of professional services that combine to make a real difference to our clients and the communities in which we work.

We are truly global. From 80 offices in 35 countries our 14,000 planners, designers, engineers and consultants deliver innovative projects across the world with creativity and passion.

Founded in 1946 with an enduring set of values, our unique trust ownership fosters a distinctive culture and an intellectual independence that encourages collaborative working. This is reflected in everything we do, allowing us to develop meaningful ideas, help shape agendas and deliver results that frequently surpass the expectations of our clients.

The people at Arup are driven to find a better way and to deliver better solutions for our clients.

We shape a better world.

The digital transformation of the construction sector is inevitable. Indeed, it has already begun. The Arup Explores programme scoured the globe for the exemplars and lessons.

Digital fabrication has been around for decades, designing with it is new. Digital fabrication was initially limited to demonstration projects, for example the Daedalus Pavilion. Recently, however, it has been applied to solve societal, industry and project challenges, for example the completion of the Sagrada Familia. It supports the quest for excellence as designers advise clients on the creation, fabrication and utilisation of their assets in the built environment.

It is seen as both a boon and a bane: it can answer novel client questions, win projects and reduce risk. On the other hand, its widespread adoption threatens to render the traditional advice of designers and project managers, referring to outdated construction techniques, redundant and potentially detrimental. Three factors are driving digital fabrication: better computer control, growing demand for complex construction with dramatically enhanced material efficiency and elimination of waste and the need for agility.

This briefing note gives a foundation about digital fabrication and the implications that this rapidly advancing field has on the industry. Our aim is to give Arup and the sector information to understand and decide how to engage with digital fabrication, appropriate to different markets, disciplines and geographies.

ARUP