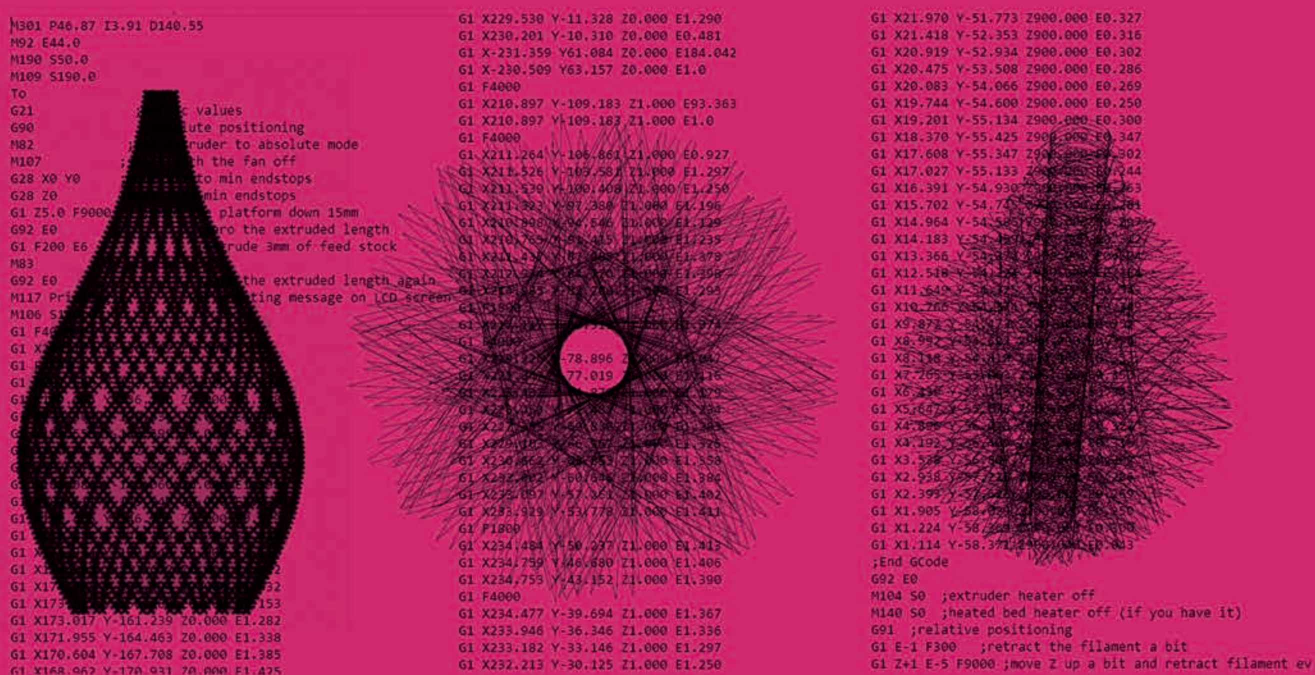
STRUCTURAL INNOVATION THROUGH DIGITAL MEANS

Wooden Waves
Galaxia
Conifera
Sandwaves
Polibot
Silkworm



ARTHUR MAMOU-MANI

UNIVERSITY OF WESTMINSTER

DESIGN RESEARCH FOLIO 2021

STRUCTURAL INNOVATION THROUGH DIGITAL MEANS

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Conifera
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Silkworm

ARTHUR MAMOU-MANI

Project: *Wooden Waves*
Location: *London*
Architect: *Mamou-Mani Ltd*
Client/Funder: *Buro Happold*
Collaborators: *Andrei Jipa, Bilal Mian*
Construction: *FabPub ltd.*
Cost: *£60,000*
Dates: *2015*

Project: *Temple Galaxia*
Location: *Black Rock City Desert, Nevada*
Architect: *Mamou-Mani Ltd*
Client/Funder: *Crowd-funded*
Collaborators: *Maialen Calleja, Aditya Bhosle, Aaron Porterfield, James Solly, Marco Pellegrino, Bruce Schena*
Construction: *Volunteers*
Cost: *US$600,000*
Dates: *2018*

Project: *Conifera*
Location: *Milan*
Architect: *Mamou-Mani Ltd*
Client/Funder: *COS*
Collaborators: *Ayham Kabbani, Nina Pestel, Maialen Calleja, Youen Perhirin, Ping-Hsiang Chen*
Construction: *FabPub ltd, SuperForma, FabLab Venezia, Design for Craft*
Cost: *£150,000*
Dates: *2019*

Project: *Sandwaves*
Location: *Riyadh, Saudi Arabia*
Architect: *Mamou-Mani Ltd*
Client/Funder: *Design Lab Experience*
Collaborators: *Studio Precht (Chris Precht, Fei Tang Precht, Andreas Stadlmayr, Zizhi You), Ayham Kabbani, Nina Pestel, Sash Onufriev, Youen Perhirin*
Construction: *FabPub ltd. (Giovanni Panico, Holly Hawkins)*
Cost: *US$400,000*
Dates: *2019*

Project: *Polibot*
Location: *London*
Architect: *Mamou-Mani Ltd*
Client/Funder: *ARUP*
Collaborators: *ARUP (Francis Archer, Andrew Edge), Ping-Hsiang Chen, Maialen Calleja, Peng Qin, Aditya Bhosle, Alex Onufriev*
Cost: *£50,000*
Dates: *2017-2020*

Project: *Silkworm*
Architect: *Adam Holloway, Arthur Mamou-Mani, Karl Kjelstrup-Johnson*
Client/Funder: *Self-initiated*
Collaborators: *Andrei Jipa*
Construction: *ongoing (v.2)*
Dates: *2013-2020*

Fig. 1
Temple Galaxia, Burning Man Festival 2018
Photo: Jamen Percy

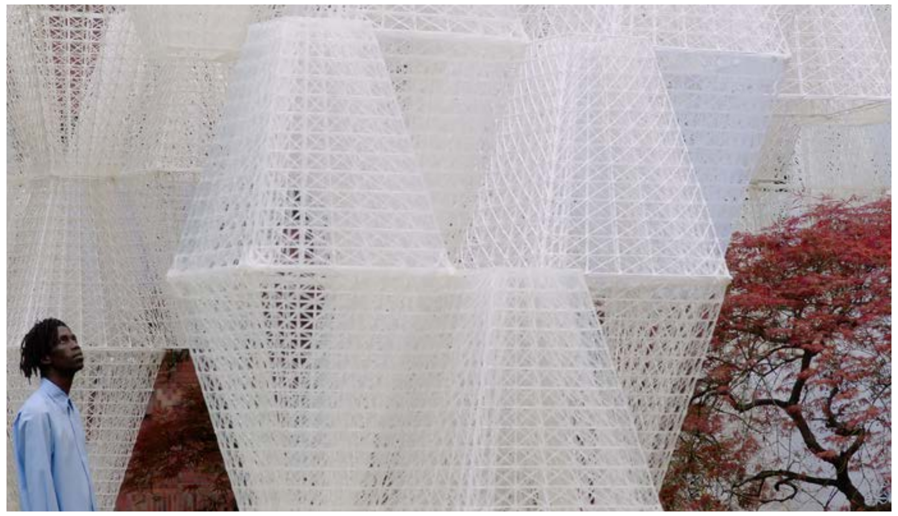


Fig. 2
Conifera, 2018

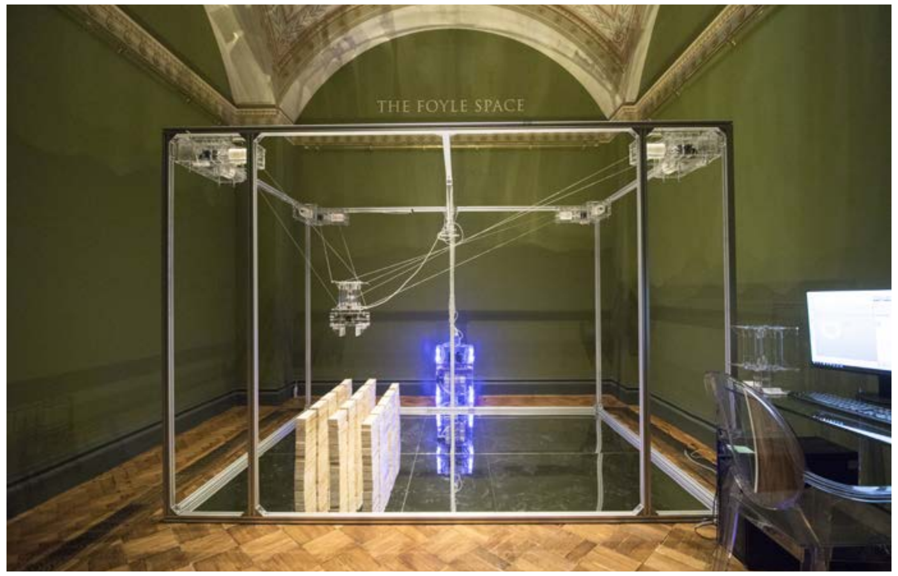


Fig. 3
Polibot, John Soane Museum, 2018

ABSTRACT

This folio comprises a body of investigation into innovative built structures developed by manipulating digital technologies to generate new structural systems, and tested using manual as well as digital construction methods.

The research was carried out through several projects, in different contexts, that were constructed at various scales, using different kinds of construction methods as well as new patterns of procurement, funding and construction management. The methods suggest a new pattern of architectural practice, construction and procurement, as well as new kinds of building and structural design in which the tools generated to make the project should be conceived as part of the project output. The research has investigated increasing moves towards more environmentally-friendly projects through re-useable and compostable structures.

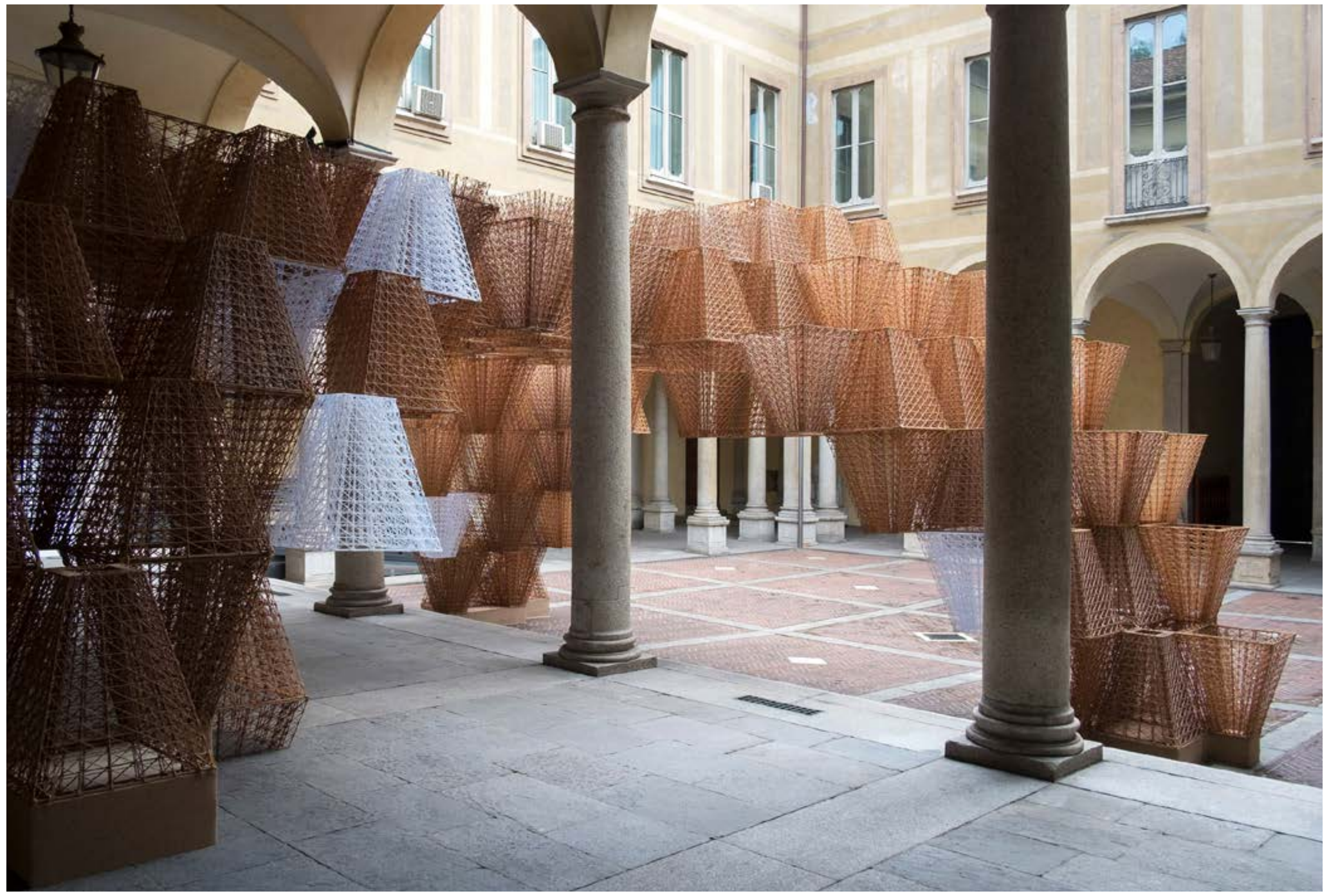
Mamou-Mani has developed this research strategy through commissioned briefs by clients and by self-initiated competition entries for large-scale permanent structures. Often the projects are inspired by patterns found in nature, and the research explores, develops, tests and expands upon these to suggest new structural models within a language of parametrics.

Notable structures included here are the installations for Buro Happold's headquarters (2015), fashion brand COS (2018) – the latter one of the largest PLA (bioplastic made from fermented sugar) 3D-printed structure in the world to date; the largest sand-printed installation to date; and, above all, the 60 metre-wide, 20 metre-high Galaxia temporary temple building erected for the 2018 Burning Man event in the USA, which was duly burned down.

Innovative procurement and construction methods have involved working with volunteers and students as well as skilled construction teams, and formulating self-generated projects that raise finance using crowd-funding platforms and 'investment angels'.

As part of this research work, Mamou-Mani has developed various forms of software innovation including, with Adam Holloway, the Silkworm plugin that exports G-Code from Grasshopper, enabling one of the world's largest 3D-printed pavilions to be created in Shanghai (Vulcan, by Yu Lei and Xu Feng).

Along with University of Westminster MArch Design Studio 10 colleague Toby Burgess, Mamou-Mani shares this new knowledge through their WeWantToLearn.net blog which has 1.6M viewers, as well as by working with volunteers, students and skilled construction teams.



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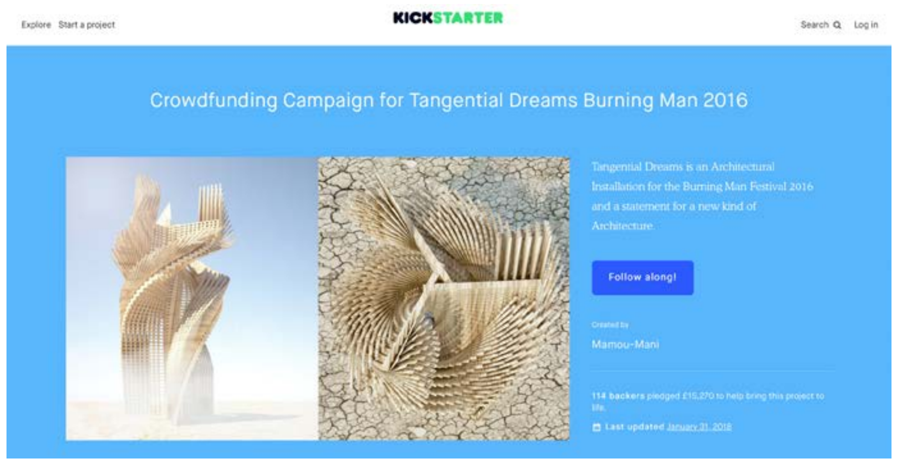

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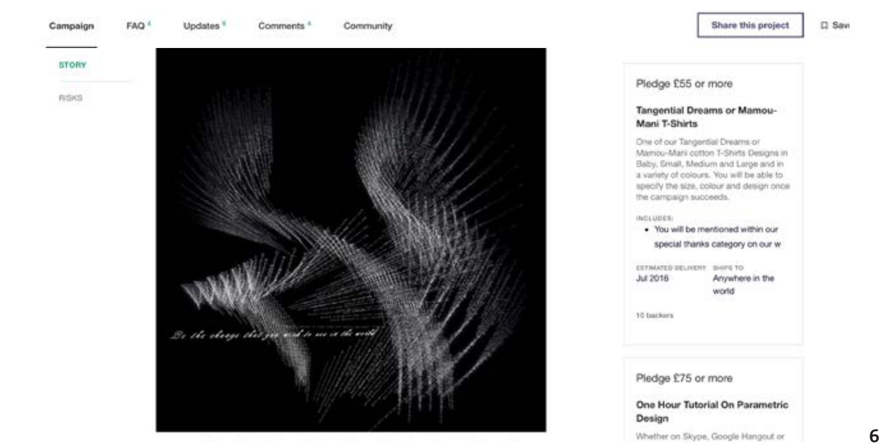

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Fig. 4
Conifera, 2018

Figs 5, 6
Crowd-funding for Burning Man, 2016

RESEARCH QUESTIONS

- What new kinds of innovative structures can be generated through emerging digital design tools and techniques; what kind of new tools can emerge in the process and how can these be tested manually and digitally through built installations?
- How may such parametric design move away from excess and towards more economical and environmentally responsible design processes and structures?
- How can new patterns of working and financing, such as architect-as-maker and tool-maker affect procurement and construction (including self-build and builds by non-specialists) when using these kinds of innovative digital projects, and how in turn might this reshape areas of architectural practice?

GENERAL DESCRIPTION

Mamou-Mani's projects are typically installations, often but not always within buildings, fabricated in its sister making company FabPub. They also include larger architectural projects (often temporary structures) and parametric consultancy for other firms. Software and robotics design and development by the practice has been central to this process and the physical projects in this folio are complemented by innovations in process and methodology.

Through each project, Mamou-Mani creates the system and the means of design rather than only finished forms. Using parametric tools, the projects are in some respects closer to a software design approach that integrates material, machines and structural performance. This loop allows the quantity of material used to be minimised by assigning the right thicknesses to the right location. The result is a very precise calibration of geometry, a paradigm shift from the standardised materials, dimensions and constant repetition typical of contemporary architecture.

This approach is combined with the idea of modularity: that each project can be prefabricated, assembled and disassembled in the spirit of the circular economy and its three key words 'Reduce, Reuse, Recycle'. Fundraising also allows Mamou-Mani to interact and engage with the community that will use the projects before building them. This can enable self-realised initiatives; the freedom to choose which project to focus on without the dependency on a client or the compromises to the design that can occur in this relationship.

The main physical projects described in this folio are:

- Wooden Waves for Buro Happold HQ, London 2015
- Galaxia for Burning Man in the Black Rock City Desert, Nevada, 2018
- Conifera for COS at the Milan Salon del Mobile 2019
- Sandwaves for DLE in Riyadh, Saudi Arabia 2019
- Polibot for ARUP (various London locations) 2017 to 2020

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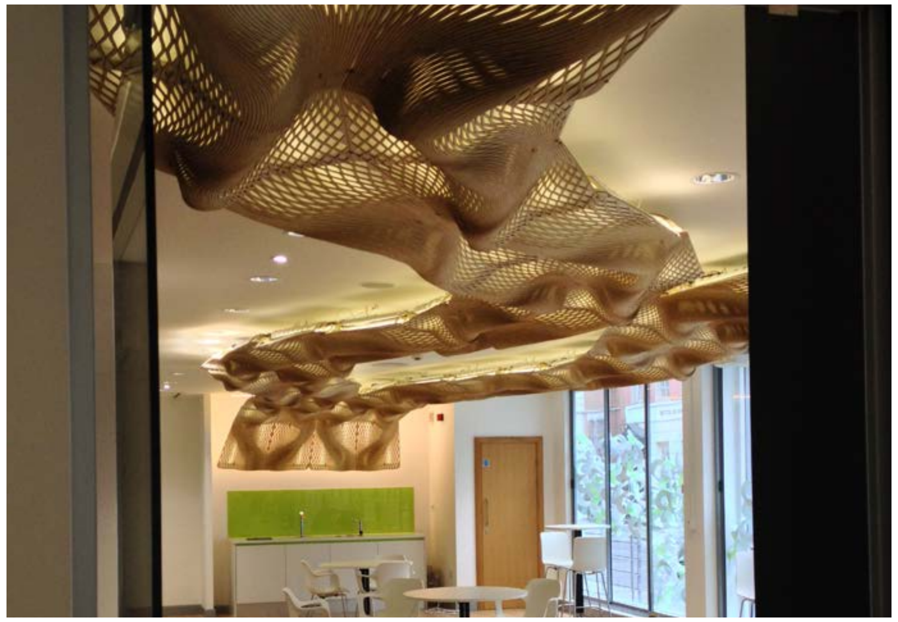

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Figs 7, 8
Wooden Waves, Buro Happold office, 2015

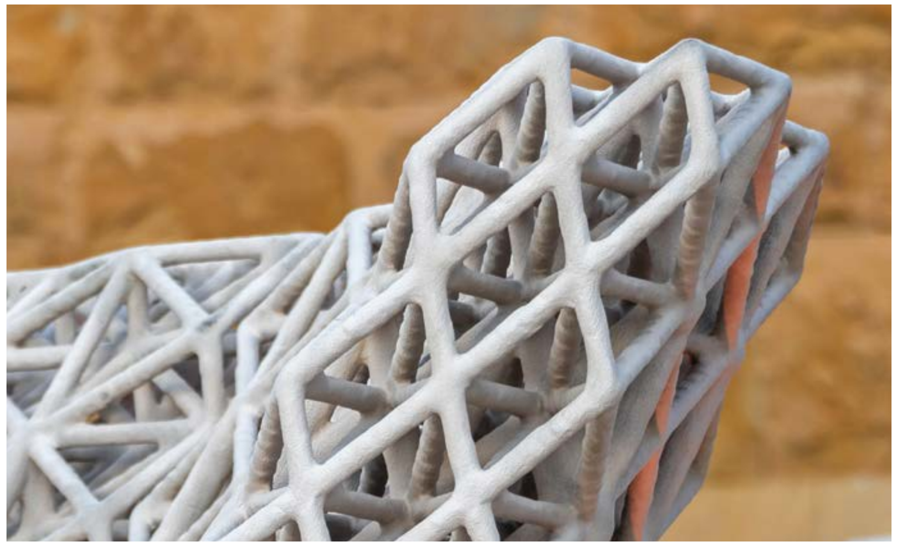

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Fig. 9
Sandwaves, Riyadh, 2019

Wooden Waves

Wooden Waves is a ceiling installation at the London headquarters of engineers Buro Happold. It is formed of 80 folded plywood panels with LEDs strips, phase-changing materials and insulative sound panels. The structure was made at the architect's fabrication laboratory in London. The components form sinuous streams folded into unexpected configurations through an open-source and innovative digital fabrication technique of 'lattice-hinge-formation'. This is a parametric pattern of laser-cut lines that alters the global properties of plywood sheets making them locally more flexible and thus controlling the 3D form without significant supporting framework.

Temple Galaxia

Galaxia was a spiralling wooden pavilion that formed the main 'temple' at the nine-day Burning Man Festival 2018 in the Black Rock City desert, before being ritually set on fire as part of the standard demolition practice at the annual event. The timber lattice structure had 20 trusses, designed to resemble petals, which leant on each other and spiralled up towards the sky around a central oculus. The design was built by 140 volunteers in 22 days.

Conifera

Digitally designed and fabricated for the 2019 Salone del Mobile (Milan Furniture Fair), the temporary Conifera installation was the largest PLA (Polylactic Acid) 3D-printed structure in the world to date. It was printed in five hours by three fablabs using Mamou-Mani's proprietary Silkworm software. Conceived as a journey from the man-made through to the natural world, and from the old to the new, Conifera was designed in response to an open brief from clothing retailer COS, and through an evolving parametric design process which integrates design, construction and robotics, where the architect is both designer and maker. The geometry of Conifera takes the square motif used throughout Palazzo Isimbardi courtyard, where the installation was staged.

Sandwaves

Sandwaves is the largest sand-printed installation to date. It was designed for the Diryah Season, a sport and entertainment festival curated by Design Lab Experience and held at Diryah at the edge of Riyadh, the capital of Saudi Arabia. Made of 58 3D-printed modular elements of sand and a resin made from the chemical compound furan, its parametric lattice thickens in response to the structural forces, forming benches which weave around palm trees, creating a calm oasis, where people can pass through under various degrees of shade. The technology creates buildings that are ecologically friendly and can respond to local cultures and building traditions.

Polibot

Polibot is a patented cable robotics system fully designed and fabricated in Mamou-Mani's studio. The robot can transform any space into a digital fabrication space. The robot builds on the 'spider cams' of sports stadia and pick-and-place technology. The Polibot prototype was funded and first exhibited at the ARUP HQ in London. It was later installed at the Tate Modern as part of the magazine *Wired* show and then in the Sir John Soane Museum, for an exhibition about the future of building construction.

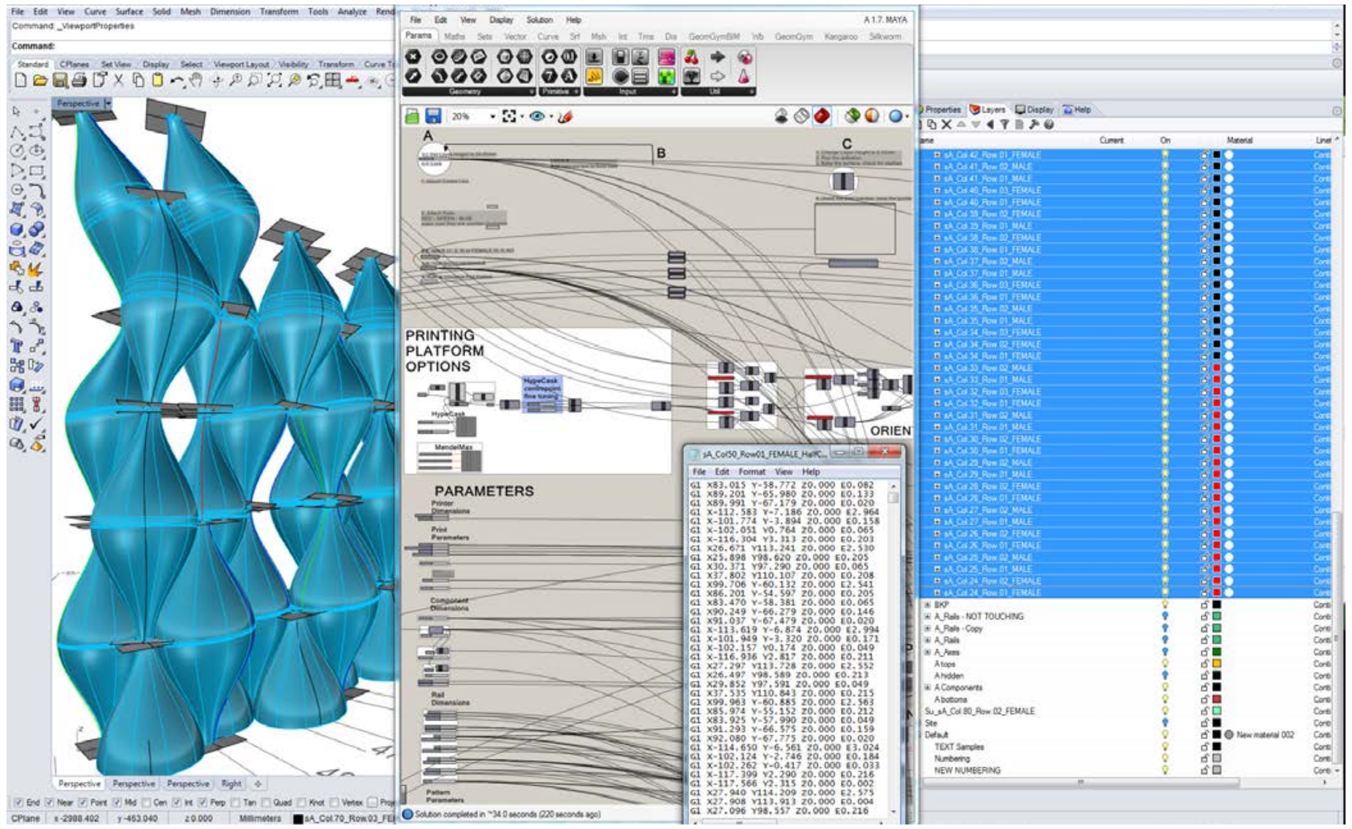

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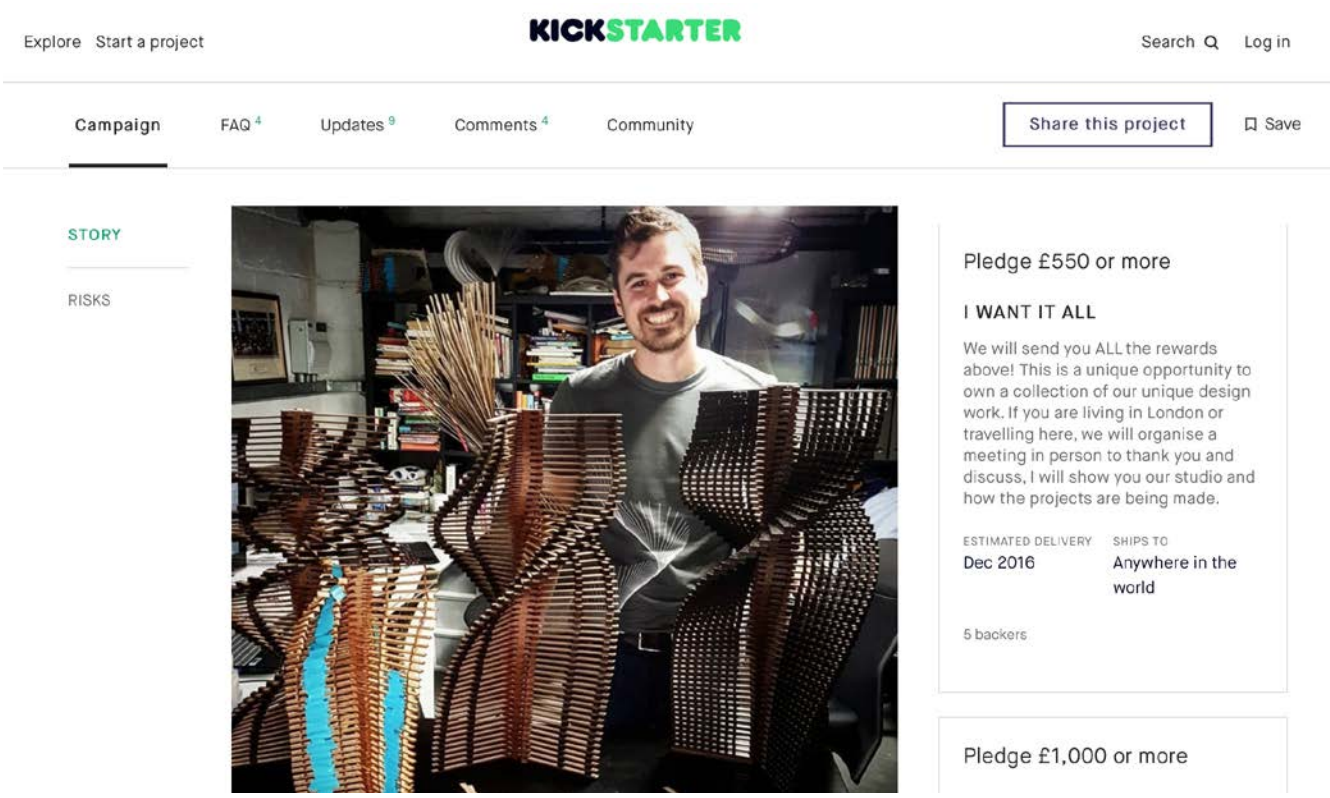
Fig. 10
Silkworm plugin for Grasshopper, Xintiandi Pop-Up Shop, Shanghai, 2015

Fig. 11
Crowdfunding for Tangential Dreams, Burning Man pavilion, 2016



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Software

The most common 3D printing workflow is to model a 3D file as a mesh and then slice it in a slicing software to create a G-code. Silkworm is a plugin for Grasshopper written in C# language, it takes any lines and applies an equation to quantify the amount of material needed for the line length. The equation is based on several variable parameters including the 3D printing nozzle width, the layer height and the filament size. Other parameters such as the feedrate can only be controlled independently and in relation to list of values that can vary throughout the geometry. Modifying the G-code throughout a geometry allows to customise a print to the properties of a geometry or a desired effect such as ‘stringing’ that Mamou-Mani used on several project such as Galaxia’s chandelier. The other benefit of Silkworm is to have a direct relationship between the output geometry and the 3D printing output. For Conifera, the speed of each print was very precise and the flow matched the layers that were implemented in the structural analysis plugin to Grasshopper called Karamba. By having several plugins work together, i.e. Karamba and Silkworm, the parametric model can compute the speed of the print in relation to the structural performance and quantity of material used. On Conifera, this resulted in a structure of 3mm throughout, for a structure of roughly 4 tonnes.

Innovative Procurement and Fundraising

Mamou-Mani’s business model has challenged in different ways the norms of architectural studios. On several projects including Galaxia and the Sandwaves, they acted as general contractor as well as fabricators and architect, managing teams of volunteers and supervising on site construction. On Galaxia, Mamou-Mani fundraised half a million dollars through high donor dinners, crowdfunding campaigns, and fundraising parties. With Polibot, Mamou-Mani patented the robot for it to become a unique product and generate royalties. On the Sandwaves, Mamou-Mani, through its sister company FabPub sold a giant 3D printer to the client to 3D print locally.

Collaborative Realisation

Working with parametric and digital fabrication tools requires a high level of collaboration. Files are shared, design algorithms are linked with structural, environmental and tool paths algorithms. All specialities are linked with the same algorithmic language through platforms such as Grasshopper for Rhinoceros and its numerous plugins. The algorithmic approach creates a convergence of specialities. It requires constant communication between architects, engineers and fabricators to enable the constant iterations that a parametric system

For the Conifera project with COS, Mamou-Mani worked with four fabrication space to deliver the project locally.

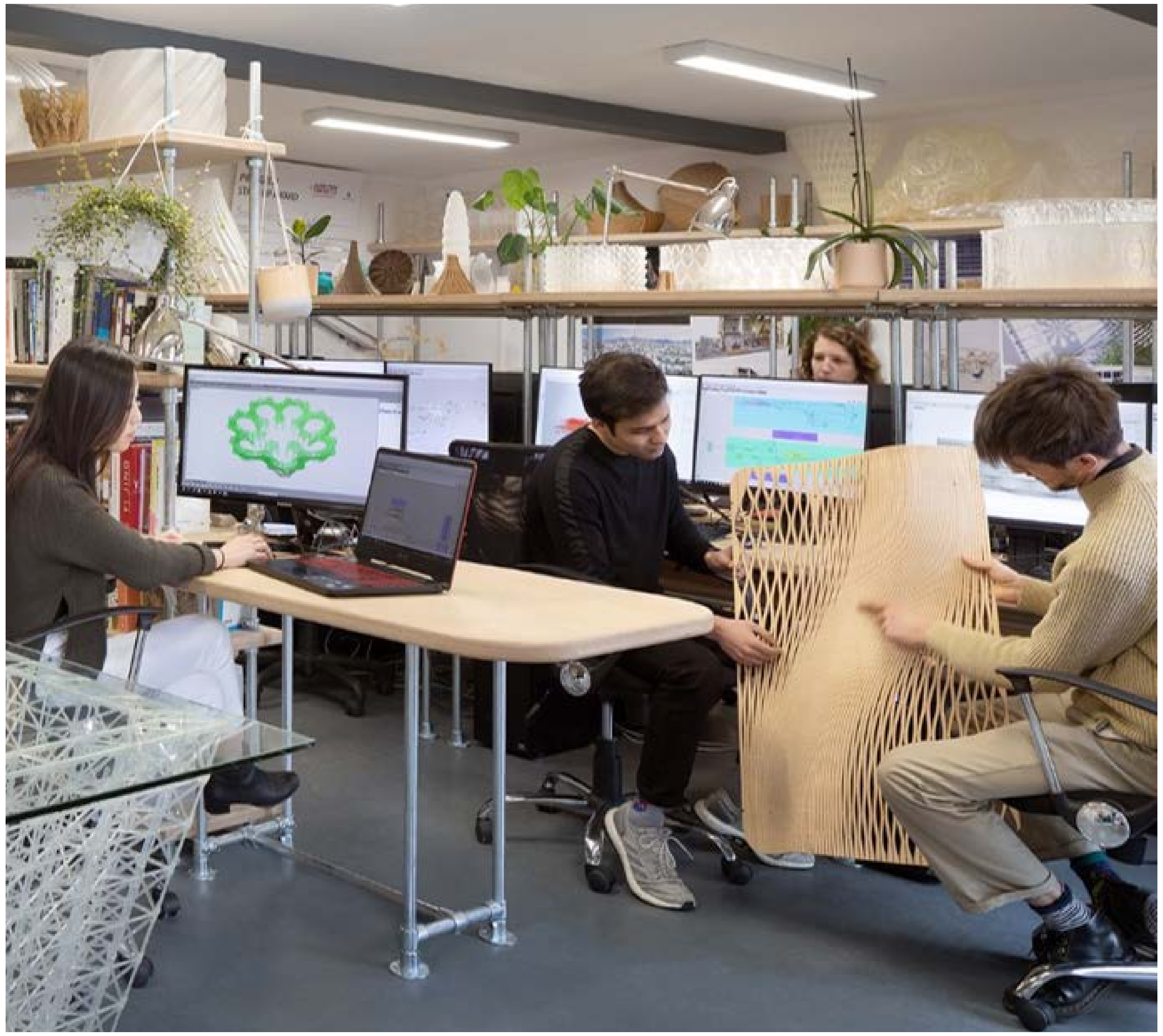

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Fig. 12
Mamou-Mani Architects office
Photo: Studio Naaro

Fig. 13
Digital fabrication at FabPub ltd.

Figs 14-15
Food Ink 3D printing Restaurant, 2016

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CONTEXT

Mamou-Mani Ltd is a RIBA chartered architectural practice founded in 2011. FabPub Ltd was established by Arthur Mamou-Mani in 2014, a fabrication company offering laser cutting and 3D printing. His is one of an emerging kind of architectural practice in which the designer is also the 'maker'. The two companies now have a dozen staff.

Digital Design and Fabrication

The projects emerge out of the development of digital parametric design in the late twentieth century based on algorithmic software and production tools that allow the expression of parameters and rules to define and encode designs' form finding. This is a progression from early computer aided design in the 1980s which was subsequently to generate form by architects such as Greg Lynn.

Digital fabrication linked with parametric design can be traced back to the early 2000's when initiatives included the linking of the software Generative Component to 3D printing, laser cutting and CNC machining at the Architectural Association's Diploma Unit 4 and the school's Emtech (Emergent Technologies and Design) programme taught by Michael Hansel, Achim Menges and Michael Weinstock. Emtech alumni included Neri Oxman, now professor at M.I.T., Andrew Kudless, Associate Professor of Architecture at the California College of the Arts in San Francisco, and Edouard Cabay, of the faculty of IAAC, in Barcelona.

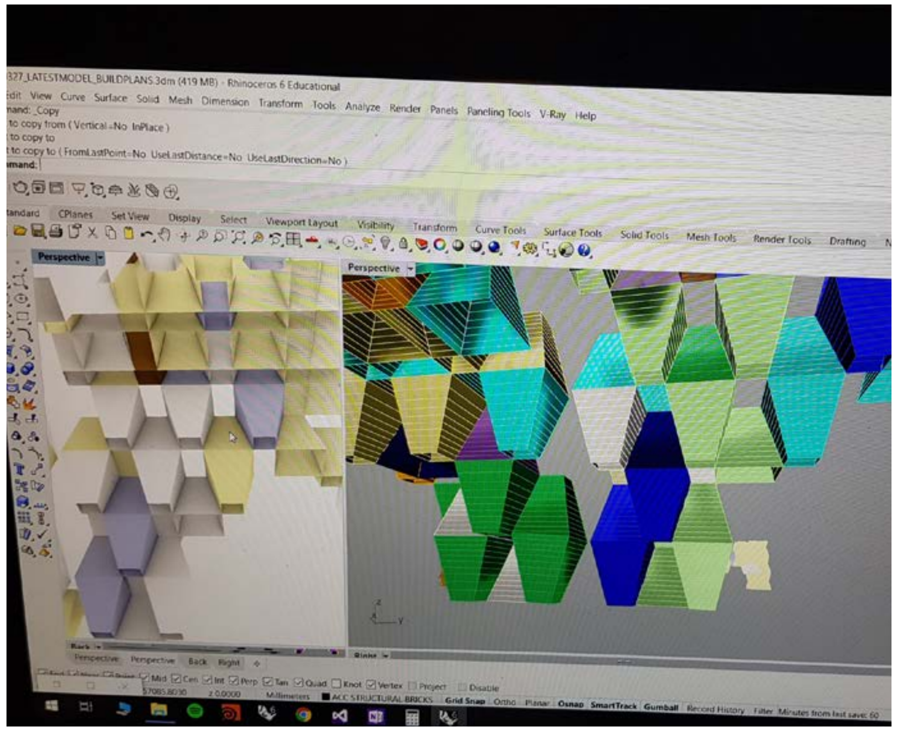
Achim Menges is now professor at the Institute for Computational Design in Stuttgart and is responsible for some of the most innovative parametrically designed and digitally fabricated structures such as the ICD/ITKE Research Pavilion 2011-2016.

In parallel, the DRL programme at the AA with Zaha Hadid Architects, pioneered the use of parametric design on the architectural scale through projects such as the Morpheus hotel in Macau. Former ZHA employees and students such as Marc Fornes (TheVeryMany), Alvin Huang (Synthesis DNA) and Chris Precht (StudioPrecht) have since redefined the use of computational tools within the architectural profession.

Practice Context

Arthur Mamou-Mani graduated in 2008 and worked for practice Proctor & Matthews where he spent two years devising a freeform biodome at Chester Zoo. He developed a parametric script that integrated the constraints of zoo professionals such as horticulturalists, vets, engineers and suppliers. Mamou-Mani became increasingly interested in 3D printing and its democratic potential when linked with parametric design. He believed that these technologies would allow more people to customise designs and therefore become more active in the making of the things they consume. His idea for a fabrication space that enabled people to rent digital fabrication machines by the hour led to FabPub (initially called People's Atelier). Mamou-Mani Ltd was founded to finance the idea.

The projects undertaken have been at a range of scales; they have been as diverse as 3D-printed food to large commissions ranging from substantial installations to the possibility of permanent buildings. Funding, too, has been innovative, from small direct commissions to crowd funding. The work is disseminated in many ways including university teaching, a sharing culture with the digital community, and by upskilling collaborators, including volunteer builders. These processes result in a working practice that is immensely more varied and open than that achieved through traditional procurement methods and RIBA contracts.



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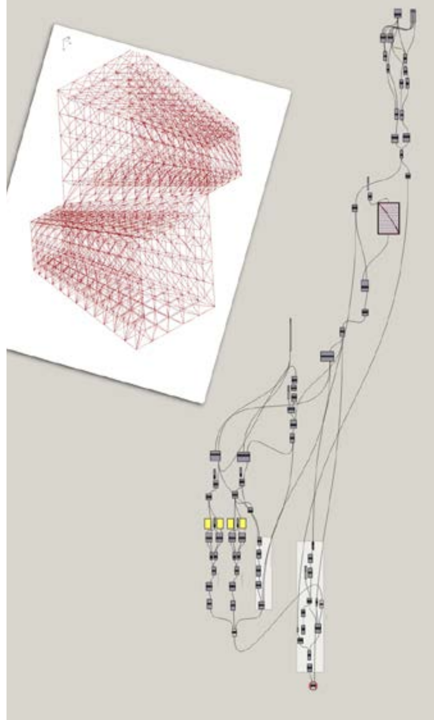

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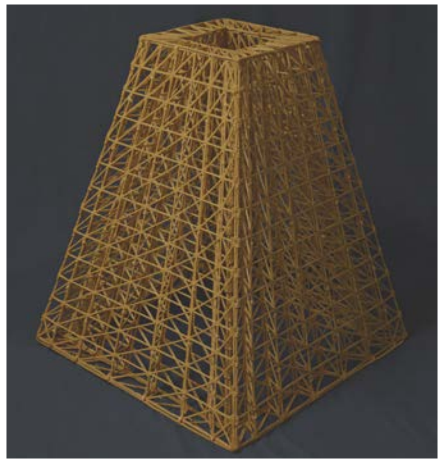
Figs 16-21
Conifera: Silkworm codes and 3D printing logistics, 2019



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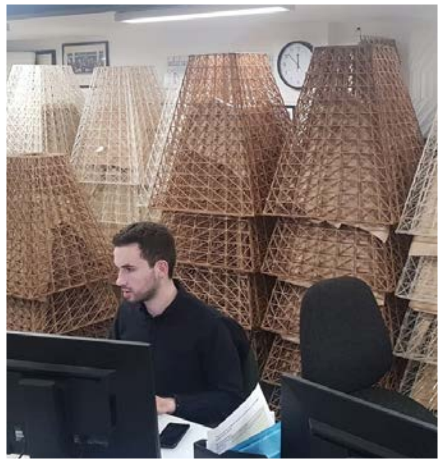

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AIMS AND OBJECTIVES

- To design software to use raw materials more efficiently by utilising parametric tools to create a system and means of design for any project, rather than necessarily specific finished forms. The aim is to allow for precise calibration of geometries that avoid the need for the standardisation of materials and constant repetition of modern architecture.
- To explore projects in ways that are closer to them being a software themselves by integrating material, machines and structural performance.
- To create custom tools that link the materials, the design and the machines, allowing projects to minimise waste and allow the creation of reusable modular structures that can be disassembled, re-used and recycled as part of a sustainable circular economy.
- To foster design projects that facilitate effective ways of working with collaborators and volunteers, and to offer an innovative way of financing that allows the practice to interact and engage with the community that will use the projects before building it. This includes exploring how 'small' units can be 'sponsored', making it easier for volunteers to participate and help create the larger scheme.

METHODOLOGY

Mamou-Mani has developed several 'means of design' such as custom software and robotic tools. This includes writing the open-source 3D printing plugin Silkworm software, and devising the universal building machine, the Polibot.

The working method importantly includes many physical prototypes and large-scale models which are used to test ways of working as well as the different applications of these tools. In this methodology, each project transforms into another one, and inform the next one. More recently, the use of Virtual Reality to test the spaces of projects is also being explored, such as in a virtual structure for Burning Man.

Entrepreneurial funding models are developed that allow design opportunities that may not be available through traditional client commissions. Mamou-Mani's two linked companies have few competitors that can combine digital innovation at this level with the machines that can realise them.

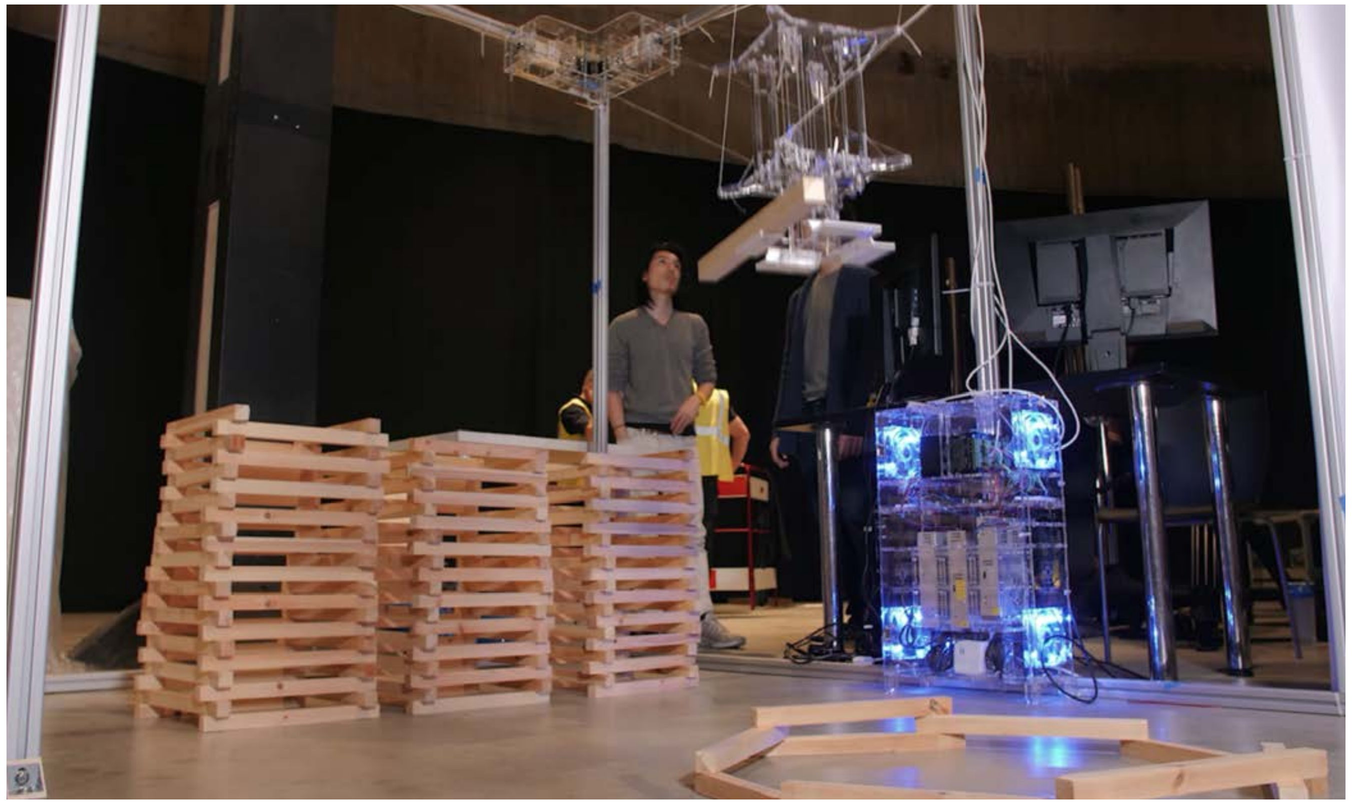
Software

Silkworm has allowed Mamou-Mani to work directly on the production of components. From the exact timing of a 3D print to the amount of material being used, the software means he has been able to link the parametric drawings to the output.

The control of the G-code (the code sent to machines for production) has enabled a new language based on varying the parameters of the specific machines to create ornamentation. For example, by alternating full extrusion and partial extrusion of

Fig. 22
WASP 3MT 3D printed at FabPub ltd.

Fig. 23
Polibot at the Tate Modern *Wired* show, 2018



bioplastic, Mamou-Mani modelled a 'stringing' effect which left a drop of material in a diagonal angle which broke the horizontal nature of the print and created unexpected structural veins.

The close link between the 'line to G-code' process of Silkworm and the output being created is so precise that Mamou-Mani's engineers, Format, were able to link their file to a structural simulation tool called Karamba and create a very lightweight solution for the Conifera project.

Fabrication

Mamou-Mani Ltd has a direct engagement in making through custom software and its fabrication sister company FabPub via the tools it develops and uses. This has established a direct link from design to output. The architecture practice thus becomes integrated with the roles and methods of craftsmen.

When using large-scale 3D printing on its projects, Mamou-Mani has sent the machine itself to the site rather than the finished objects. Examples include the Shanghai Xintiandi Pop-Up Studio (2014) and the 2017 Code Builder exhibition at London's Sir John Soane Museum which continued to print during the event.

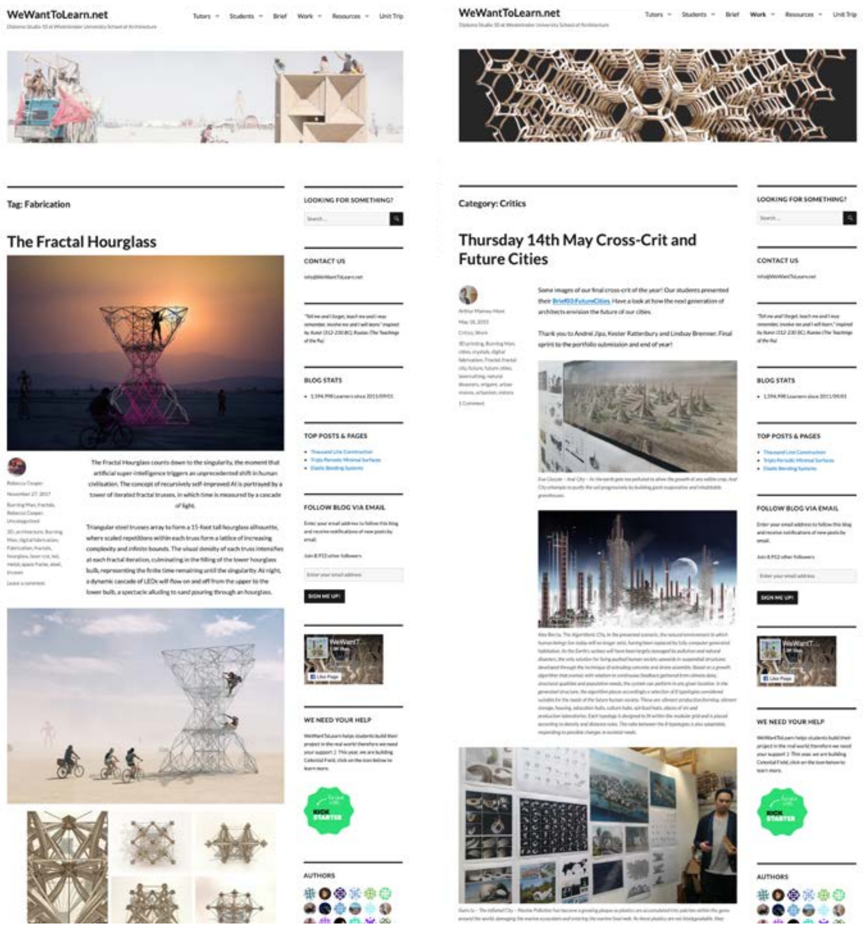
Mamou-Mani has also worked very closely with fabrication spaces (fablabs) close to sites through what is known as 'distributed manufacturing', reducing the carbon footprint involved in the act of delivery.

The patented Polibot allows any space to be turned into a digital fabrication machine by combining the concept of a stadium spider cam with a 3D printer. It is a 'universal building machine' fully designed and built in the studio. Building on the 'spider cams' of sports stadia and pick-and-place technology, the crane and cable robot can assemble and disassemble modular structures. It was conceived as a response to the difficulties of transporting large-scale 3D printers which are not, in any case, suited to tall structures or materials other than plastics.

Funding

Many of Mamou-Mani's projects are crowdfunded or the result of external investment such as Galaxia and Tangential Dreams. The latter project was partially funded by Burning Man (US$20,000) and the remaining US$15,000 were funded by a kickstarter campaign. Tangential Dreams was a climbable sinuous tower made from off-the-shelf timber and digitally designed via algorithmic rules. One thousand 'tangents', or wooden pieces, were stencilled with inspirational messages which people had been invited to send in advance through the kickstarter campaign reward system. During the event, people would look for their tangent and others would write replies to the messages, turning the project into an evolving dialogue.

Galaxia was funded through a crowdfunding campaign on the online platform Hatchfund in which the project and its needs were explained in a video. Through the site, people would give a certain amount against 'rewards' which ranged from jewellery pieces all the way to private visits of the project with the architect.



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Figs 24, 25
wewanttolearn.net screen grabs and contributors

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FabPub itself was funded by external investors ('business angels') following a business plan prepared by the architect. These alternative entrepreneurial methods of funding are an intentional step away from the more usual 'client pays, architect does' model. It gives the freedom to propose innovative projects to the general public with all the risks and rewards given to the architect (such as the patent for the Polibot).

Knowledge Sharing and Building

Knowledge sharing and building is a conscious component of the methodology – enabling users to become skilled in using the tools and methods and growing future markets. For MArch Design Studio 10 at the University of Westminster Arthur Mamou-Mani and Toby Burgess have developed a blog called WeWantToLearn.net (visited more than 1.5 million times). The blog is used as a platform for current and past students to publish their research openly. This has led to many collaborations and opportunities for students and tutors. For example, Wooden Wave at Buro Happold's London office was developed from a wider initiative in which students created architectural pieces displayed throughout the office.

Fig. 26
Volunteers building Galaxia, 2018

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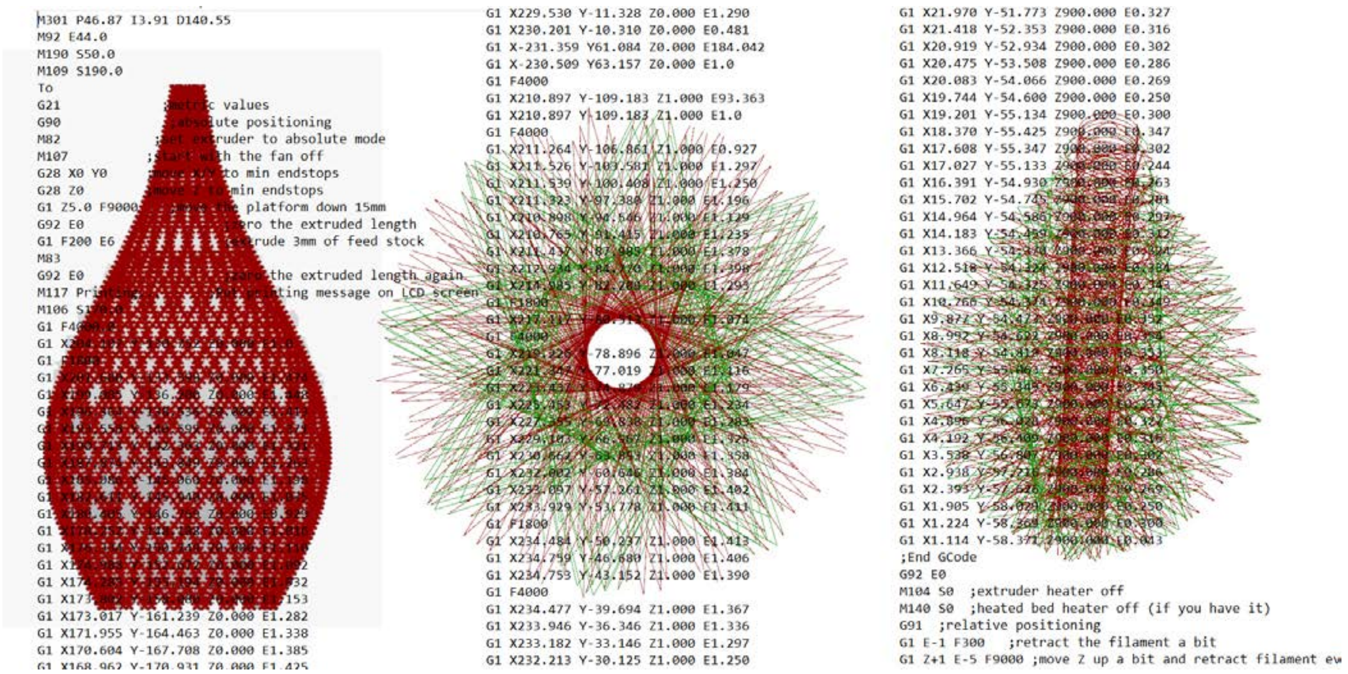


Fig. 27
Silkworm G-code and digital representations of the forms it would create, Bilal Mian, 2018

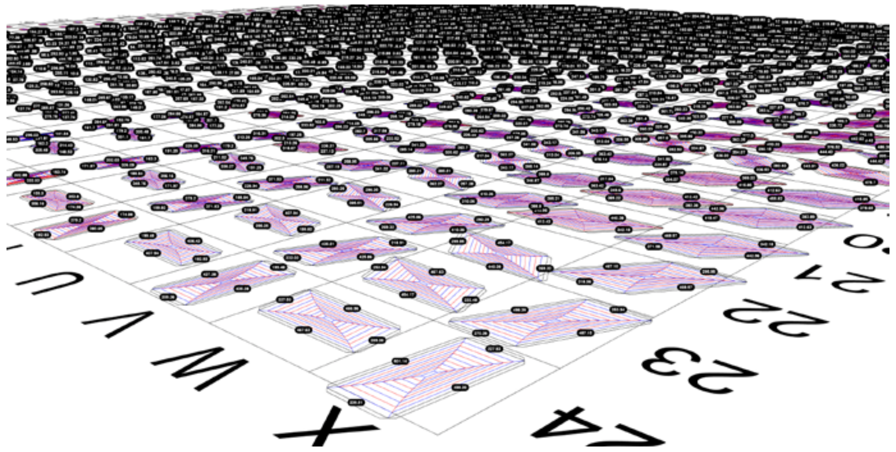


Fig. 28
Using parametric tools to create fabrication files, The Blue Origami (with ARUP Associates), Shanghai, 2014

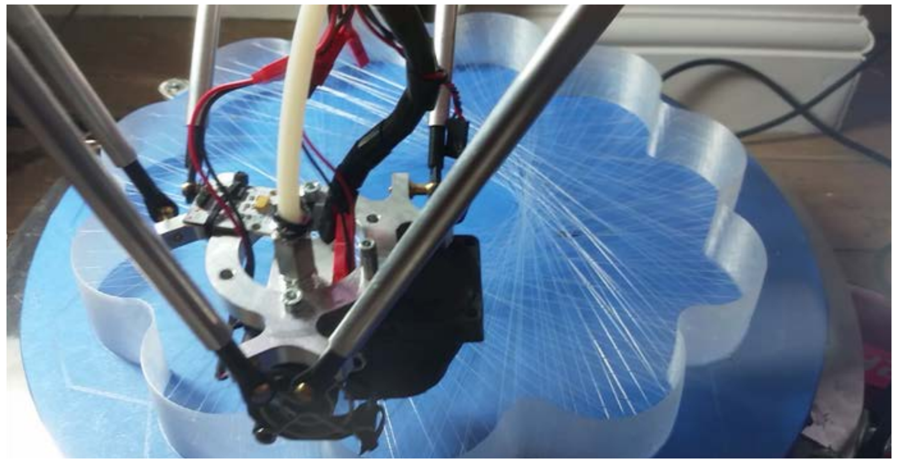


Fig. 29
3D printing in mid-air using silkworm coding, The Cloud Capsules, 2014

OUTPUTS AND FINDINGS

The complementary projects and innovative tools and processes explored here form a body of work that is at the leading edge of sustainable parametric design, as well as innovative procurement and construction methods that offer the possibility of profound architectural change. The learning from this work is routinely and extensively disseminated through direct-to-user digital platforms as well as through more traditionally authenticated platforms, reinforcing the possibilities for wider adoption of new technologies. While many of the built structures are not occupied buildings and some are of a limited scale, they offer demonstrable steps towards scaling up such innovations, as well as an innovative method of architectural practice including entrepreneurship as well as demonstrating the role of the architect as inventor and maker.

Silkworm Software

Silkworm changes the long-standing use of a 3D printer's G-Code – the numerical control programming language responsible for every printing movement.

Project Silkworm was launched by Arthur Mamou-Mani with Adam Holloway. Mamou-Mani and Karl Kjelstrup-Johnson manipulate a printer's G-code while still using CAD software, allowing for customisable inputs, for instance translating Grasshopper and Rhino geometry into the G-Code needed to print. Silkworm gives designers the capability of controlling the flow from the extruder, equating to thicker or thinner extrusions, as well as better control of the exact paths of deposition and speed. For example, intricate weaves can be produced using varying extrusion widths and print speeds, and contours such as wood grain or single layer spirals become possible.

By generating the G-code directly from vectors rather than surfaces one can control the order in which the printer moves rather than relying on a third-party software that applies generic algorithms. The path can match the printer that we use, it can match the geometry that we print, the material that we use, the extrusion can be varied depending on structural need. On the Conifera project Mamou-Mani got the thickness of each structural member to be consistent throughout (and linked with the structural calculations) by linking the layer height and extrusion flow directly with the tool path. With this approach, the geometry is the tool path. Therefore, the line-based structural calculations were closely linked with the output and allowed the user to only use the material that is strictly necessary.

The plugin and the whole C# code were made freely available under a Creative Commons License.

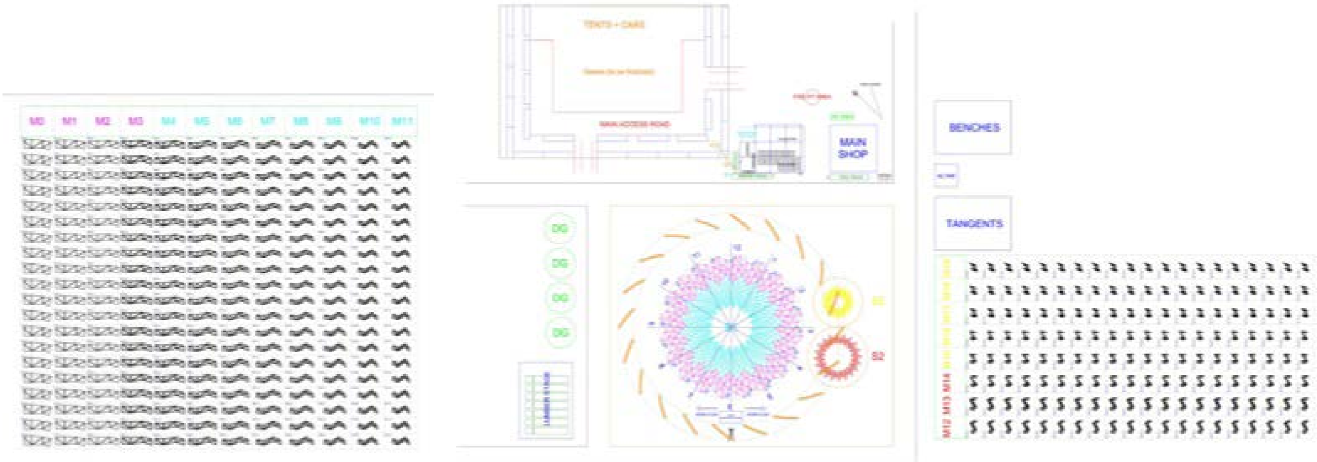


Fig. 30
Master plan of Galaxia's build camp and site, 2018

Polibot Robotics

The Polibot is a 'universal building machine' fully designed and built in the studio. It builds on the 'spider cams' of sports stadia and pick-and-place technology and was conceived in response to the difficulties of transporting large-scale 3D printers which are not, in any case, suited to creating tall structures or to work in materials such as timber or masonry, but just plastics. Mamou-Mani investigated cable robotics that are portable, can be used with various construction materials and can be readily hoisted into position. He secured seed funding via a competition run by Arup.

The Polibot is a network of cotton ropes controlled by four digitally operated motors. It can autonomously assemble or disassemble modular structures by picking and placing components. A Kinect sensor enables the robot to place modules. An interchangeable head means that it could be fitted with a 3D-printing extruder. Future versions of the robot could see the potential for the erection of entire buildings including tall buildings. It can also transform any space into a digital fabrication space.

The Polibot was first exhibited at ARUP's London HQ and was later installed at the Tate Modern as part of a Wired Magazine show at Tate Modern and then in the Sir John Soane Museum in an exhibition dedicated to the practice's work. Mamou-Mani is now evolving his own company structure to start selling the patented Polibot as a product, looking at potential distributors and partners.

A theoretical project is the Blockchain Tower, a proposal for a building that can build and unbuild itself using a larger version of the Polibot cable robot and custom-designed timber container-like office modules. The idea came from seeing tall skyscrapers staying empty during economic crises and from Mamou-Mani's office, which is located in a shipping container workspace complex.

Fig. 31
Wooden Waves installation initial parametric model, Buro Happold, 2015

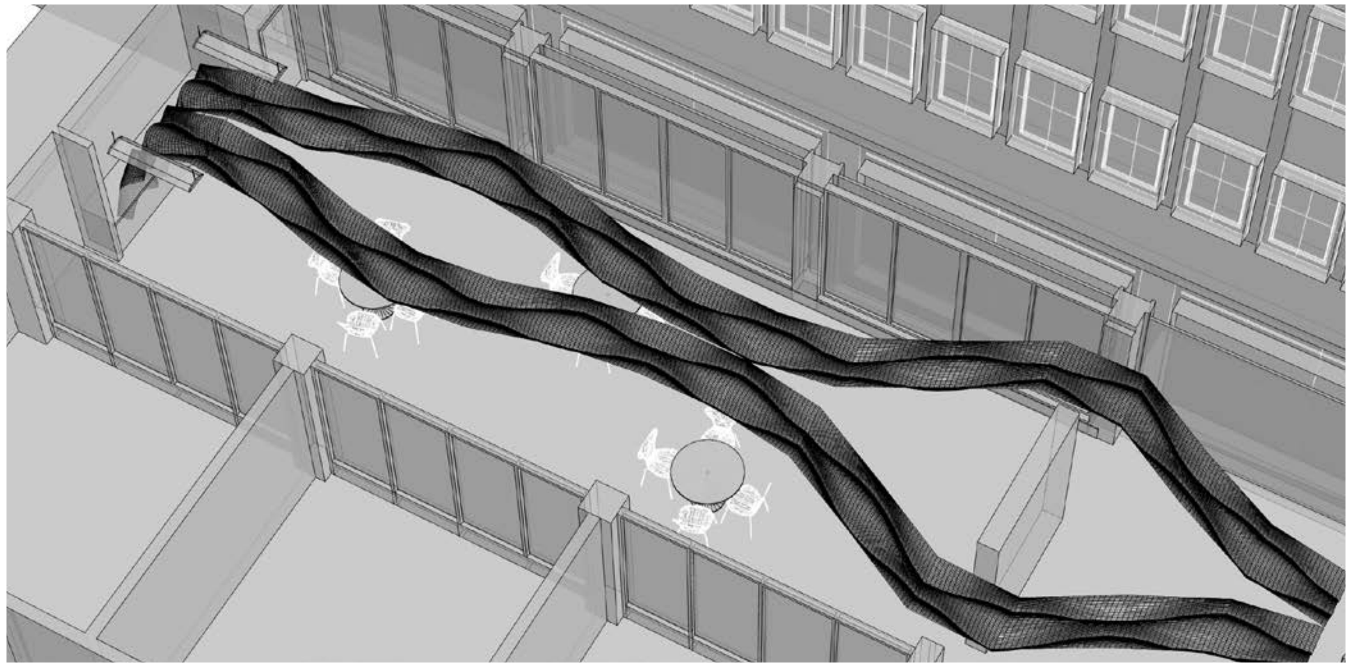
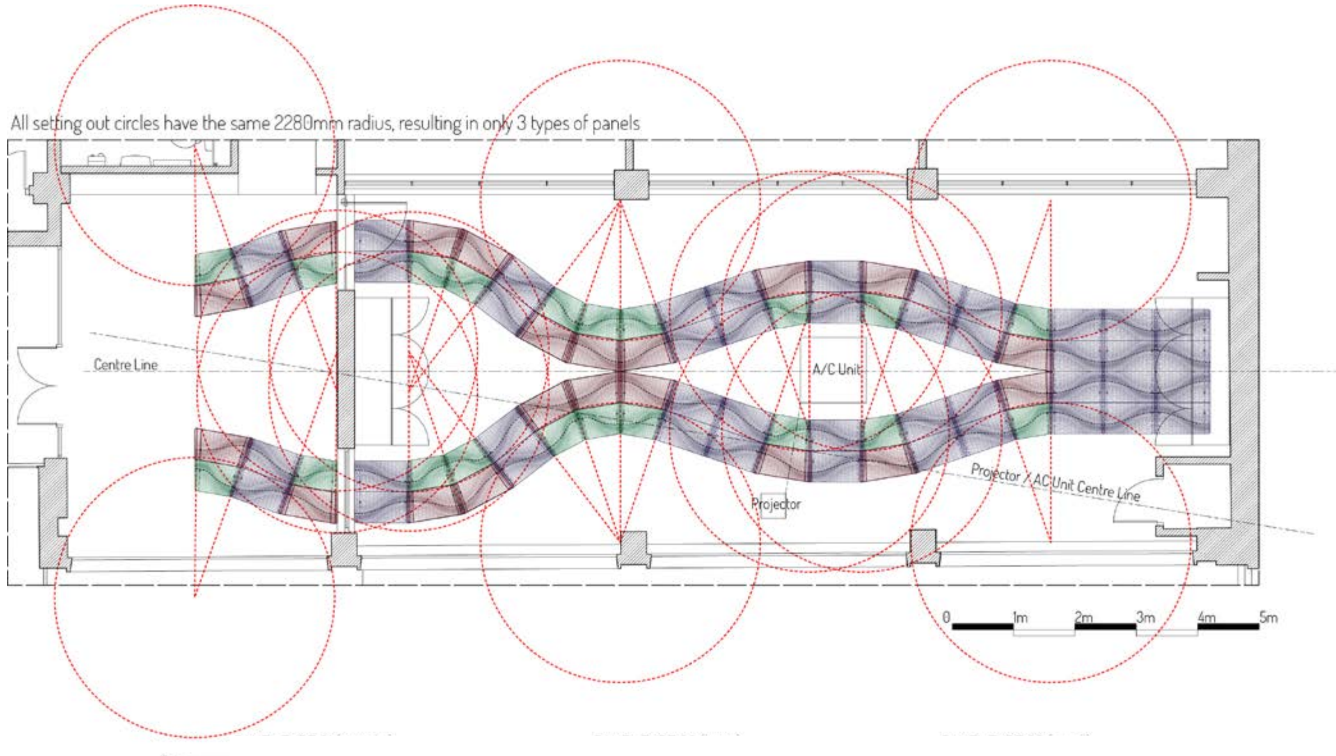
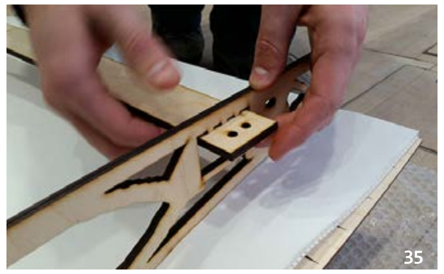
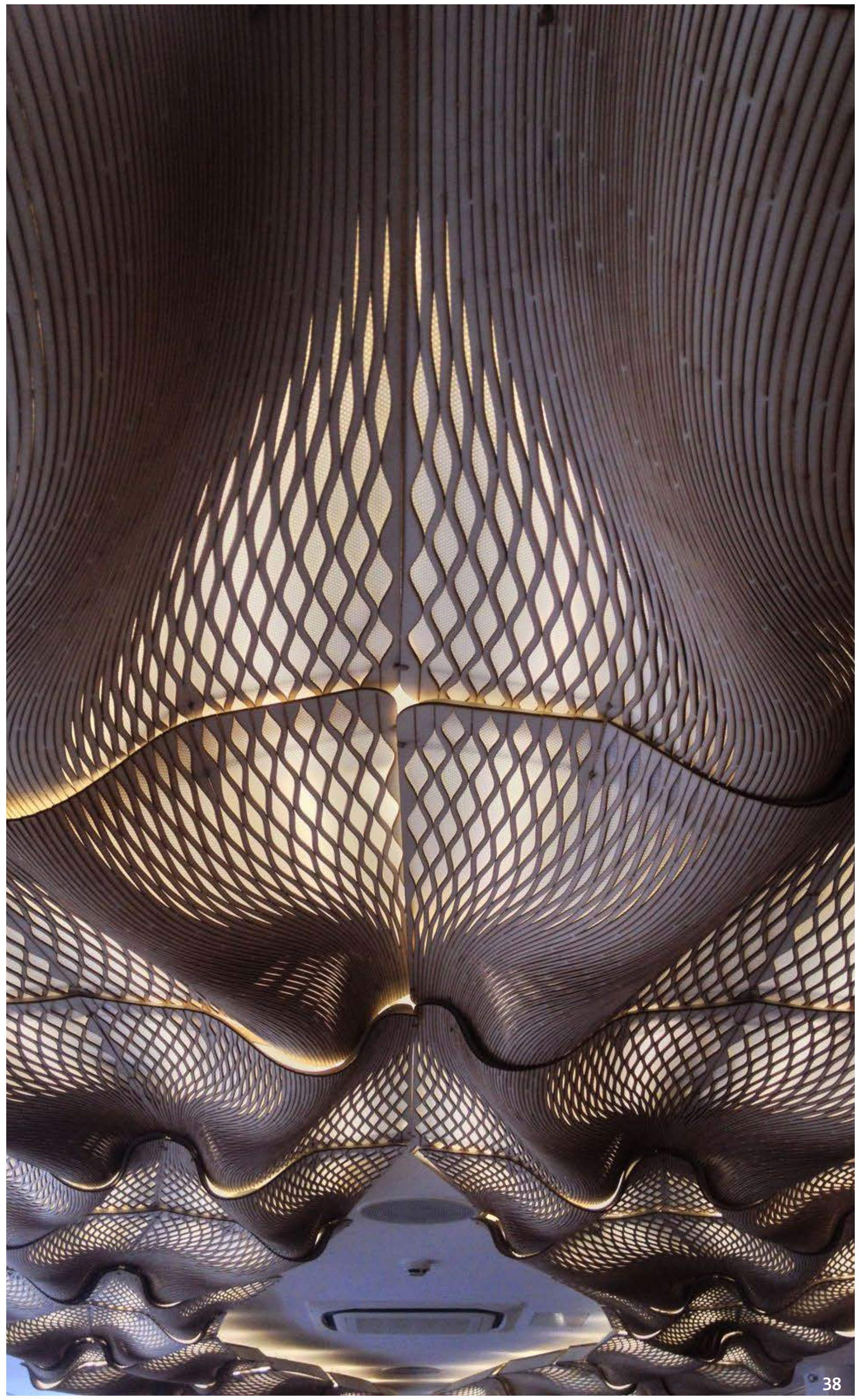
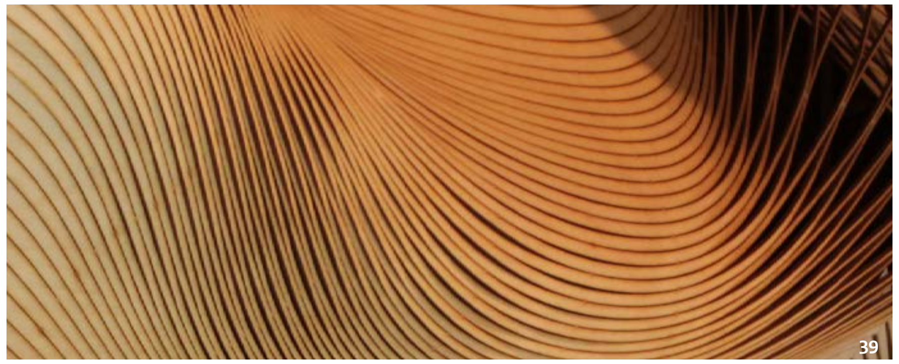


Fig. 32
Wooden Waves installation, optimised parametric model, Buro Happold, 2015









Figs 33-39
Wooden Waves installation assembly and details, Buro Happold, 2015

Wooden Waves

The client's brief was for an intimate break-out zone within Buro Happold's newly refurbished HQ in London using featured components that could represent the engineering company's commitment to timber and technology. The scheme needed to allow the development of complex forms which could be constructed economically from lightweight, cheap and portable materials.

Built from plywood, the structure was made at the architect's fabrication laboratory in London. Its components form sinuous plywood 'streams' that fold into unexpected configurations through an open-source and innovative digital fabrication technique of 'lattice-hinge-formation'. This is a parametric pattern of laser-cut lines which alters the global properties of plywood sheets making them locally more flexible, and thus controlling the 3D form without significant supporting framework.

The lattice hinge method is a development of the traditional timber bending technique, using the beam-width of the laser to kerf the material to form torsional springs. Eighty folded plywood panels with LEDs strips were used in the ceiling installation, incorporating phase-changing materials and sound-insulating panels into the design which improve the acoustics and stabilise temperature. Diffuse light thus filters through the modules' cuts, which open when bent.

The project was completed in several stages. Mamou-Mani used the laser cutter to create three prototypes with different parametric openings for the client to choose between. Being the designer and maker of the project allowed Mamou-Mani to iterate and create unique solutions adapting to the space while using the same parametric, material and fabrication logic.

The project was later reused in a different form for a private apartment in Miami, thus turning a site-specific project into a product with wider appeal, and contributing to an evolution of the architect's business model.

Fig. 40
Wooden Waves re-installation, Miami, 2019

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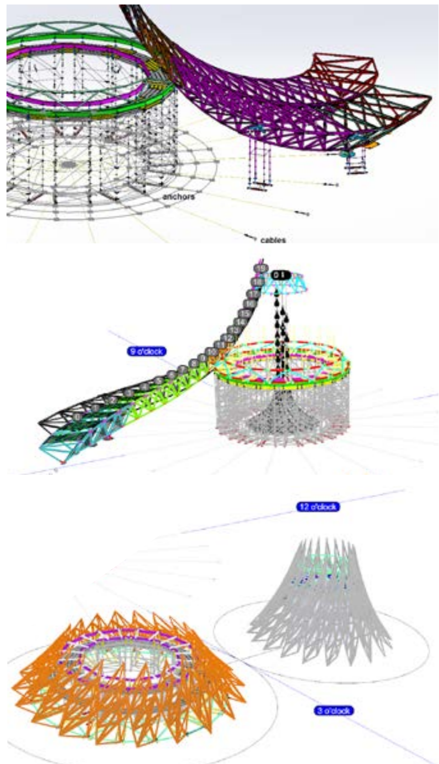

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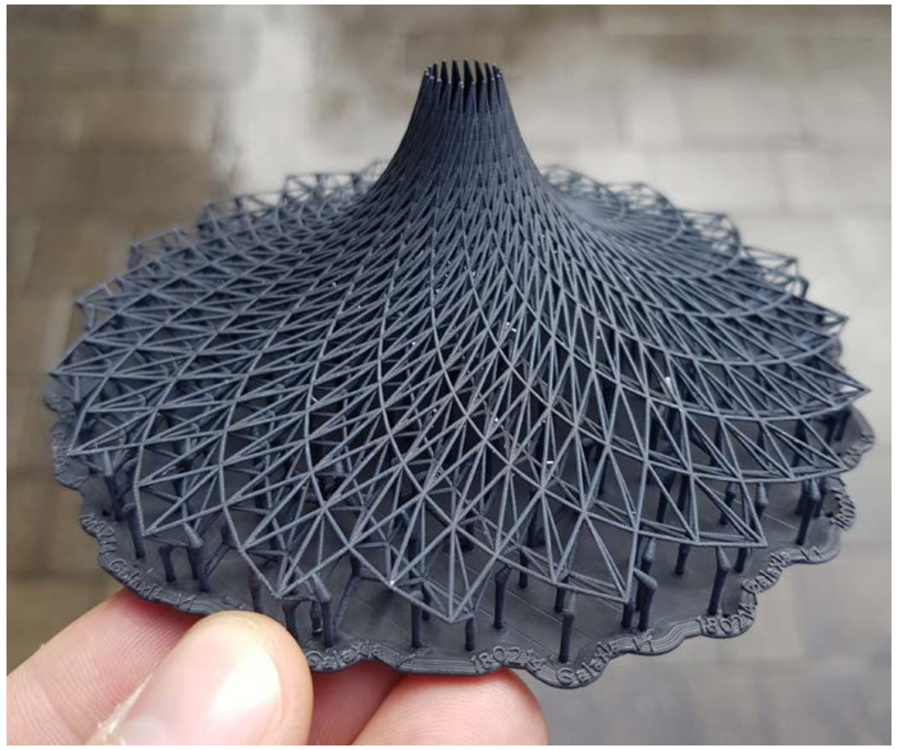
Fig. 41
Galaxia structure testing, The Generator, Reno, USA, 2018

Fig. 42
Galaxia build sequence logistics models with scaffolding, 2018

Figs 43, 44
Building Galaxia with 140 volunteers in 22 days, 2018
Photo (Fig. 44): Andro Antonades



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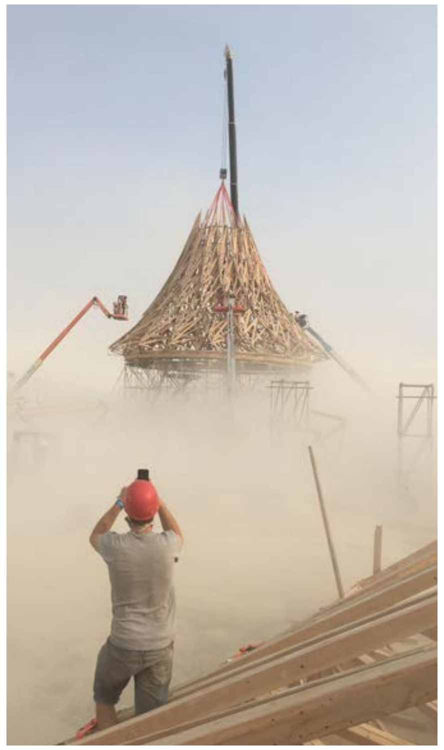

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Galaxia for Burning Man

Galaxia is a spiralling wooden pavilion that was the main temple at the 2018 Burning Man Festival in the Black Rock City desert. The temple was Burning Man Festival's 'portal' for healing, sharing emotional experiences, creating profound emotional connections, and offering a place for the community to pray, heal and release grief, before watching it be ritually set on fire on the last day.

The timber lattice structure had 20 trusses designed to look like petals, which leant on each other and spiralled up towards the sky around a central oculus. The triangular trusses created small alcoves and paths into the centre of the secular temple, where a giant 3D-printed mandala was placed.

The main challenge of Galaxia was to combine off-the-shelf material with computational design techniques, in a way that could be responsive to available funding and constructed by minimally-trained volunteers.

Galaxia was completed in 22 days in the desert with 140 volunteers, although the pre-fabrication started in April in two different locations in the U.S.A. The remote teamwork happened through collaborative task platform Slack which allowed separate channels for each one of the many topics to cover for the project (fundraising, foundations, build sequencing, etc.). Organising volunteer work was extremely challenging across different time zones. However iterative design development did prove possible. For example, the head carpenter of the San Francisco build site recommended the use of the 'crease angle' to measure the angle between two planes. As part of the 'volunteer-friendly', approach, each module was designed as a module to be folded collectively and assembled together with ratchet straps.

Once built, the project weighed around 100 tonnes including 60 tonnes of wood for a surface of 3000m^2, and the structure cost \$200/m^2, which is extremely light and inexpensive for a project of this scale. The lightness was created by maximising tensile elements in the structure by orienting the truss to the optimal direction. A cable foundation also reduced the amount of steel being used; akin to a bike wheel, it could be adjusted on site, unlike the originally conceived fixed pile foundations.

Galaxia was designed with time in mind. Every component was placed to eliminate obstacles to the build sequence. For example, the cables supporting the structure had to align with the scaffolding. The project was divided into teams of skilled and unskilled builders and the educational aspect of the project was essential, with daily safety briefings.


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Figs 45-50
Building, Burning, Recycling: Galaxia, 2018
Photos: Bruce Schena, Matthew Gilbuena, John Curley, Jamen Percy, Mike Filippof, Arthur Mamou-Mani


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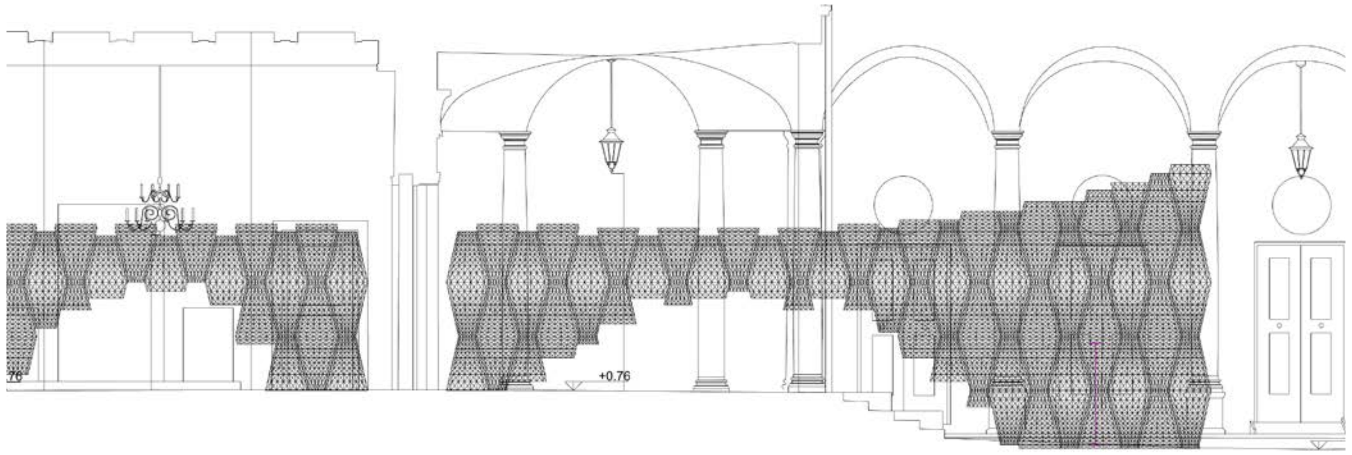

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Conifera Digitally designed and fabricated, Conifera is the largest PLA 3D-printed structure in the world to date. It was created from seven hundred interlocking modular bio-bricks, 3D printed in a mix of wood and bioplastic. It was installed at the Palazzi Isimbardi, a seventeenth-century palace, once used by Mussolini and now used by the municipality of Milan.

Conifera reflects a new generation of architecture, showcasing advances in material innovation, technology and creativity. The installation is formed in modules that shift from a wood and bioplastic composite in the courtyard through to translucent bioplastic in the palazzo's garden. Each bio-brick is made from fully compostable resources printed in the form of interlocking structural lattices, optimising material use and allowing light to permeate the structure as visitors travel through the installation. 700 modules were printed (five hours for each) in three Italian fabrication laboratories using Silkworm. Each bio brick weighed 4kg with a cross section of 3mm, yet was able to support more than 150kg and was part of a structure that weighed 4.5 tonnes. Each brick was 800mm high by 700mm wide and could be described geometrically as truncated pyramid.

Conceived as a journey from the manmade through to the natural world, and from the old to the new, Conifera was designed in response to an open brief from COS, and through an evolving parametric design process which integrates design construction and robotics, where the architect is both designer and maker. Inspired by patterns within the palazzo's architecture, the geometry of Conifera takes the square motif used throughout Palazzo Isimbardi from the courtyard to the tiles, and realises this in compostable materials made of sawdust and sugar.

Conifera was the most 'Instagrammed' project of the 2019 Milan Design Week. According to Mamou-Mani this is due to the piece's modularity and the variety of perspective the truncated pyramids can provide. Akin to many vanishing points, they allow the viewer (and their camera) to frame the context in many different ways.

According to client feedback, the project influenced COS as a company to push itself to reflect on carbon emitting practices and usage of material more broadly.


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Figs 51-54
Conifera: most 'instagrammed' installation in Milan 2019, design and installation

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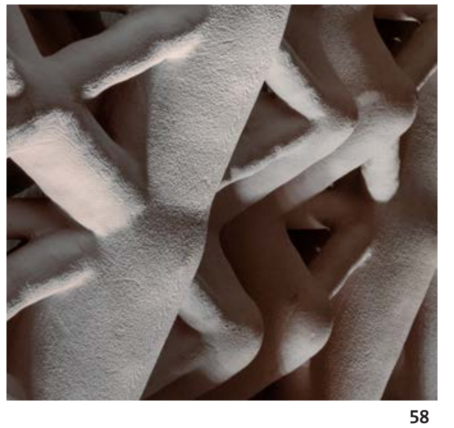

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Sandwaves

A modular urban installation, Sandwaves is the largest sand-printed installation to date. It was designed for the Diryah Season sports and entertainment festival held at the edge of Riyadh, the Saudi Arabian capital, and curated by Design Lab Experience. The brief was for a temporary project to be used as urban furniture for the festival, and to demonstrate how 3D printing with local materials can help implement a 'cradle-to-cradle' approach to architecture.

The installation was made of 58 3D-printed elements of sand and furan (a chemical compound) resin. The parametric lattice thickens in response to the structural forces, forming benches which weave around palm trees, creating a calm oasis, where people can pass through, or stop and reflect. The lattice changes in thickness depending on the forces going through it, similarly to the veins of a leaf. The modules are thus perforated, expressing an honest portrait of their structural capabilities, as well as creating different shades of transparency along the length of the pavilion.

Each module of the Sandwaves weighed 160kg. There were two types printed, in pairs, in a mirrored position within a sand base. Once printed layer by layer, the pieces were dug out of the sand, like archaeological artefacts.

By using local materials combined with cutting edge technology, Sandwaves demonstrates a technology that can create buildings that are ecologically friendly and respond to a local culture and building traditions.

The project had its origins in discussions at Munster University, Germany, where Austrian architect Chris Precht had invited Arthur Mamou-Mani for a crit and a lecture. Precht was subsequently the conduit for the Saudi project. The pair found a company that could 3D print in sand in Riyadh and decided to create a series of modules made using this technology – a direct example of innovative design research arising directly from teaching.

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Figs 55-59
Sandwaves: construction and after installation
Photos: Roberto Conte

Fig. 60
Team building Galaxia

CRITICAL SELF-APPRAISAL

The projects have developed through a growing and acknowledged need for increasing environmental consciousness. Some principles were developed from the ethos of the Burning Man festival which was originally seen as an ideal testing ground for such structural innovations. Later works have shifted to principles of lifetime designs, where products can be re-used, de-assembled, or fully recycled.

This work has, however, faced controversies. Galaxia was burnt as part of a ritual that helps a community of 70,000 mourn and let go, but it is acknowledged that the $600,000 structure could have been disassembled instead. The fire itself only generated four tons of carbon, from that locked in the timber and the recycled steel used. For this reason, Mamou-Mani has since created the Catharsis amphitheatre originally planned for Burning Man 2020, a modular building that would have been assembled and taken down to be rebuilt at Somerset House in London.

Another challenge was around the use and promotion of bioplastics for the Conifera project. The blog *Dezeen* published a post saying that bioplastics were worse than petroleum-based plastics. However, this stems from a misunderstanding in the difference between biodegradability and composting. Bioplastics cannot be disposed of as if it would disappear with time and instead need to be placed in an industrial compost which heats the PLA to 60° under 100% humidity for a few months prior to the material becoming earth.

Using digital fabrication tools also constrains the size of what can be done. However, this is also an opportunity for a modular design, which has not typically been seen as a key aspect of parametricism, but which, given the widespread availability of 3D printers, seems highly significant. For Mamou-Mani, there is also a symbolic quality in having multiples of one element to form a structure, as expressing an idea of 'together we are stronger' and emphasising collective aspects of design, construction and use in this work.

The workings of practice and experimentation have made the entrepreneurial approach more or less inevitable. While it allows innovation it also raises new problems (e.g.. unpaid volunteer labour etc.) as well as new opportunities (e.g.. new types of building). At the same time, the growth of small scale/brick modules which facilitate 3D printing at small scales allows a small office to design and build complex structures.

The iterative dissemination of accrued knowledge and innovations becomes possible through the interrelation of the paired companies and the integrated teaching of the tools to the wider community. This dissemination and teaching allows innovation to spread and also creates new opportunities for it. While the Westminster University teaching Design Studio is not narrowly seen as allowable research, student work has been an active part of and contribution to these research projects, offering both iterative testing of principles and software as well as the very wide sharing and development of work through the extensive WeWantToLearn.net website.

DISSEMINATION, ACHIEVEMENTS, PEER REVIEW

Books

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Code Builder: Mamou Mani Retrospective, Soane Museum, London, 5 December 2018 - 3 February 2019.

MILAN Conifera, COS, Salone del Mobile, Milan Design Fair, Palazzo Isimbardi, Milan, 9-14 April 2019.

30,000 visitors over a week, it was the most visited COS installation so far and the most instagrammed piece that year. It was built as part of the Milan Design Fair in April 2019.

Burning Man is an event taking place yearly at the end of August in Black Rock Desert, Nevada U.S.A, Galaxia was the official temple for the year 2018.

Film

Art on Fire (2020). Dir: Gerrald Fox.

Awards

Emerging Architect of the Year 2018, RIBA Journal (Winner)

Emerging Architect of the Year, 2019, *Dezeen* (Shortlisted)

American Architecture Prize, 2016 (Wooden Waves, Gold Prize in Interiors category)

Architizer A+ Award, 2017 ('Tangential Dreams, Burning Man, 2016, popular choice winner).

Dezeen Awards, 2019. (Galaxia, highly commended small building of the year)

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