FABRICATE

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FABRICATE 2024

CREATING RESOURCEFUL FUTURES

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FOREWORD

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In an era where anthropogenic materials surpass the weight of all life on Earth, and the construction sector stands as a major agent of ecological disruption, advancements in digital technologies present a paradigm-shifting opportunity to revolutionise the way we conceive, design, and build our environments. In this context, FABRICATE has become more pertinent and opportune than ever.

Since its inception in 2011, FABRICATE has positioned making and digital fabrication at the forefront of research and education in contemporary architecture and design. It has evolved over the years, seeking to unveil ways of scaling up and releasing from the lab novel design and fabrication processes that can address the ongoing ecological emergency.

Yet, FABRICATE 2024 aims not merely to celebrate greater cutting-edge innovations in digital fabrication and computational design than its predecessors. The contents of this volume represent a meticulously curated selection embodying what could be considered a radical paradigm shift in design and production for the built environment.

At the core of this paradigm shift is the activation of responses to the challenge of resource scarcity through unconventional lenses. In a context of hyper-growth coupled with the climate emergency, rapid urbanisation, and heightened social and political awareness concerning the Anthropocene, the discourse on resource depletion and insufficiency is being reframed through the lens of abundance rather than that of scarcity. Strategies such as the use of reclaimed materials, design for disassembly, upcycling waste for construction, urban mining, or the reuse of existing building stock, among other proposals showcased in this volume, land principles of the circular economy at the heart of design and construction. Operating with an abundance mindset not only redefines how we perceive resources and materialise buildings, but also encourages risk-taking in the Architecture, Engineering, and Construction industry, promoting growth, interdisciplinary collaboration, and innovation.

The *abundance* design paradigm does not limit itself to novel design and manufacturing processes for legibly reconstituting matter and improving the performance of material assemblies to allow reuse. The diverse projects presented in this volume pose the challenge of designing and building with material libraries shifting towards organic and natural consistencies or even towards living matter synthetically created for growth and harvesting. Biomaterials, including composites, aggregates, or fibres, which are cast, 3D-printed, wound , or synthetically grown, are found in every selection for this volume. They not only mitigate the carbon-intensive impacts of our building industries, but, more significantly, promote a restorative, decarbonising paradigm for design and production. Biomaterials encourage innovative manufacturing and design as much as they boost new economic models (bioeconomy), novel forest and land management processes, and ethical decisions for design and construction that protect communities at risk from resource extraction. Such paradigms could disrupt 'business as usual' in the built environment, excluding agents that benefit from the climate crisis in favour of those that do not.

FABRICATE, since its inception, has deliberated novel technologies that can influence design and manufacturing. In this edition, sophisticated processes for human-machine collaboration, building components of live matter, as well as mobile machines for on-site fabrication or bespoke 3D printers for high-performance hybrid building envelopes and structures, are all examples of a unique fusion of human, machine, and inter-species intelligence. The outcome is a distinctive collective intelligence design paradigm that empowers the applications of co-creation, following generative processes of both the living and the machine.

The question, however, revolves around whether, as discipline and society, we are ready to embrace the profound impact of this paradigm shift. Even if, for the sake of research and experimentation, we decide to overlook the reality that the construction industry is a low-innovation and negligibly digitised sector, several issues continue to demand collective reflection and action.

What happens to form when it follows availability? If unifying form is a bygone paradigm, how can scalability be achieved for marketable processes in industrial production?

In an era of shrinking natural resources, does 'reclaiming' proclaim the emergence of new standards for habitation and aesthetics? What about standards that challenge polished finishes, redefine building lifecycles, and introduce new metabolic processes, textures, visions, and smells? Which species are genuinely prepared for this?

How accessible and open are these processes and technologies, really? How do political regimes or shifting economic conditions influence decisions for development in the built environment, and which parts of the world benefit the most?

While FABRICATE 2024 does not intend to provide specific answers to these questions, the event and this publication are together evidence that can contribute to arguments, negotiations, and informed decisions for positive change in how, and for whom, we design and build. From farming matter to harvesting expired building components, FABRICATE 2024 promotes a design and making paradigm shift that not only redefines how we perceive resources, but also has the potential to irrevocably transform traditional approaches to urban development, building protocols, and planetary inhabitation modes.

ACKNOWLEDGEMENTS

METTE RAMSGAARD THOMSEN / PHIL AYRES / BOB SHEIL / MARILENA SKAVARA
EDITORS / FABRICATE: CREATING RESOURCEFUL FUTURES

We have many friends and colleagues to acknowledge and wish to start with our warmest thanks to our returning partners Blumer Lehman and ARUP, both of whom support FABRICATE through content, sponsorship, expertise, and exchange. To the Realdania Foundation, Cowifonden Foundation, Statens Kunstfond Foundation, and the Carlsberg Foundation, we express our sincere appreciation for their generous and transformational financial support. Denmark is privileged to have such a robust and extensive landscape of foundations to support research, practice, and dissemination across industry and the arts.

In equal measure we thank the FABRICATE community for its continued passion and engagement with the subject matter and this event in particular. From this community we received more than 250 submissions from 45 countries; we would like to thank everyone who responded to the call for the extraordinary breadth, depth, and quality of work submitted, which made the process of review, selection, and curatorship extremely challenging. We are grateful to all authors and collaborators on each of the projects selected, and to all those who generously agreed to present their work.

We are deeply appreciative of our wonderful 2024 and 2020 keynote presenters in turn, not only for your provocative orations, but also for your generosity in sharing the insights and perspectives published as the Dialogues in this book. We are indebted to kindred communities for their willingness to promote FABRICATE; this includes the ACADIA, LINA, CAFx and Rhino communities. Our thanks extend to our media partners *ArchDaily*, *Dezeen* and *Actar/urbanNext*.

Our sincere gratitude is extended to The Royal Danish Academy for supporting this great enterprise. We thank our Rector Lene Dammand Lund, our Dean of the Architecture School Jakob Knudsen, and our Head of Institute Natalie Mossin, for opening the campus at Holmen to host this event. Sincere thanks must be directed also to the academy's IT team, to Flemming Steen Pedersen in particular, and to our campus service team for energetically attending to many of the practicalities that remain hidden when a project is efficiently managed. Our gratitude is expressed to the 2024 cohort of Computation in Architecture Master's students for their generous help on the ground in the lead up to and running of the conference.

Moving to the inner circle, first and foremost, thank you to co-editor Marilena Skavara who has been involved in every event and production since 2011, and whose astute strategic judgement, impeccable management, aesthetic prowess, and meticulous oversight ensures the quality and consistency of the entire project. None of this would be possible without Marilena's key role and contribution. Our thanks also to Pernille Maria Bärnheim who has been instrumental in building awareness of the event and interfacing our aims and intentions with external parties, from keynote speakers, to media partners, to extended communities and beyond.

We wish to thank the following who have helped us assemble this impressive publication: Patrick Morrissey, our meticulous designer who, for the third time has added elegant, fresh, and subtle augmentations to the template; his supreme gifts as a visual storyteller in selecting and grading each paper's sequence of figures is central to the book's legacy. We thank and welcome as new colleagues, Jill Weintroub our copyeditor, and Karen Francis our proofreader, both of whom have collaborated and executed their forensic tasks with patience and alacrity. Thank you, once again, to Chris Penfold, Lara Speicher, Alison Fox, and Jamiee Biggins of UCL Press, publishers of the FABRICATE series as the widely acclaimed open access publication it has become; and to Srijana Gurung of the Bartlett communications team for her help with further disseminating the hardback copies in the UK. We are grateful to Riverside Architectural Press for their important role of distributing the publication in North America.

Our thanks to those responsible for the tactile experience that you, as reader, are enjoying now: to Albe de Coker printers, we salute your passion for craft and detail, and deeply appreciate your kindness and tolerance – qualities that are vital in the making of well-made things.

Finally, we would like to thank all our fellow peer reviewers for their invaluable contribution and generosity in ensuring the highest research standards across the FABRICATE 2024 selection process: Sean Ahlquist, Ana Maria Anton, Philip Beesley, Philippe Block, Jane Burry, Paolo Cascone, Nat Chard, Canhui Chen, Brandon Clifford, Xavier De Kestellier, Klaas De Rycke, Pradeep Devadass, Benjamin Dillenburger, Stylianos Dritsas, Nick Dunn, Stephen Gage, Ruairi Glynn, Fabio Gramazio, Matthias (Hank) Haeusler, Ingrid Halland, Sean Hanna, Alvin Huang, Markus Matthias Hudert, Anja Jonkhans, Axel Kilian, Chris Knapp, Jan Knippers, Toni Kotnik, Silke Langenberg, Chris Leung, Tim Lucas, Mathilde Marengo, Areti Markopoulou, Wes McGee, Achim Menges, Catie Newell, Paul Nicholas, Kas Oosterhuis, Mariana Popescu, Arthur Prior, Dagmar Reinhardt, Gilles Retsin, Jenny Sabin, Virginia San Fratello, Fabian Scheurer, Roland Snooks, Asbjørn Søndergaard, Hanno Stehling, Tom Svilans, Skylar Tibbits, Edoardo Tibuzzi, Kathy Velikov, Emmanuel Vercruysse, Petras Vestartas and Oliver Wilton.

INTRODUCTION
FABRICATE 2024: CREATING RESOURCEFUL FUTURES

METTE RAMSGAARD THOMSEN / PHIL AYRES / BOB SHEIL / MARILENA SKAVARA
EDITORS / FABRICATE: CREATING RESOURCEFUL FUTURES

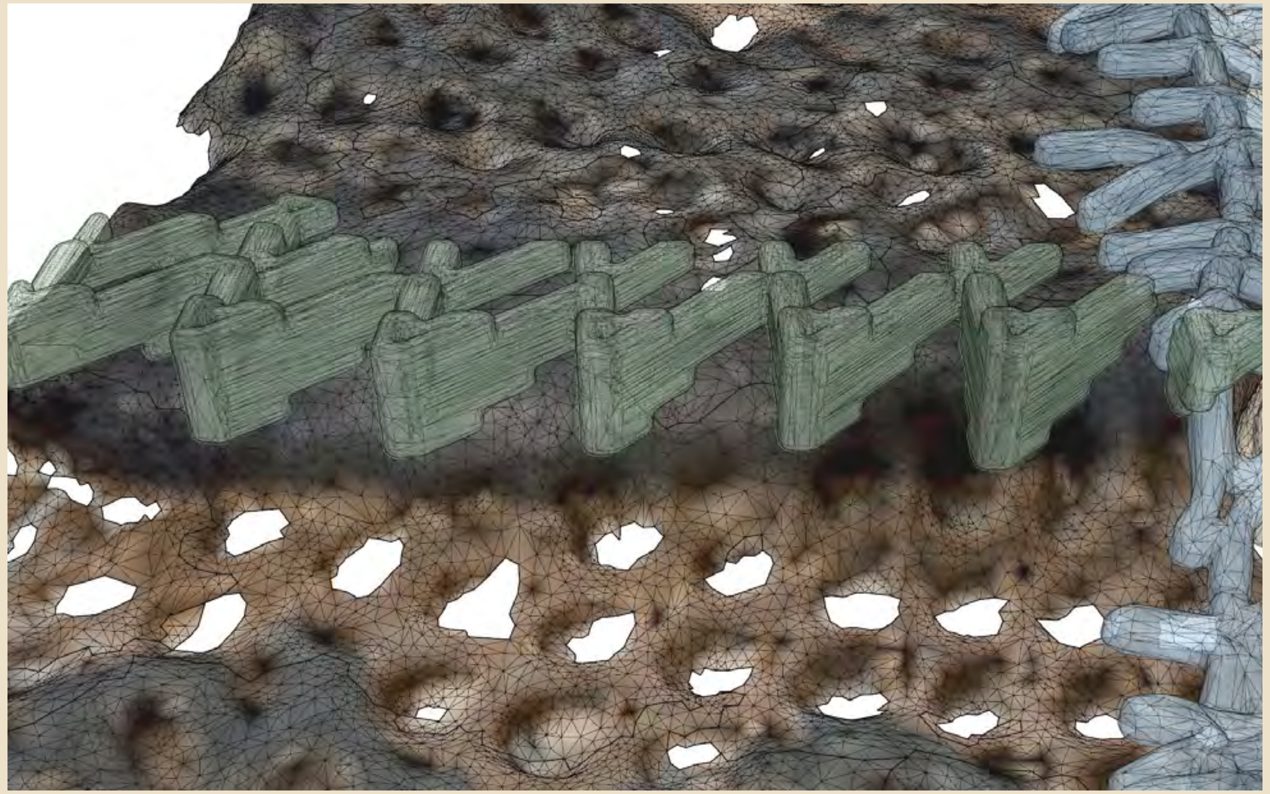
FABRICATE 2024 marks a watershed moment. Collectively, we stand at a juncture where conventional methods of resource acquisition and industrial production are recognised and quantified as primary contributors to ecological disruption. At the same time, there is a pressing need to meet the demand for additional construction while maintaining and improving the existing building stock – all within a context of intensifying resource scarcity and meagre carbon budgets. The interdependency and complexity of this multifaceted set of issues presents a significant provocation to developing coherent and meaningful responses, all of which require deep transformations within an industry renowned for its risk adversity and caution to disruptive change.

For us as architects, engineers, and constructors of the built environment, a primary lever for addressing these challenges lies with a critical consideration of the materials we use to fabricate the built environment. But their scale and complexity also demands that we undertake a profound interrogation of the methodological underpinnings that guide design practice and research. These underpinnings shape systematic and disciplined enquiries into materials, as well as the fabrication processes that we employ to transform them into built structures.

This interrogation is driving research and development into ways of reducing the impacts and quantities of use of conventional materials while extending their lifespans and reconceptualising them as valuable resources that can be reclaimed and reused in future constructions. Our material base is being expanded into novel resource streams with particular attention directed towards the renewable and regenerative. As such, our methods of evaluating environmental impacts of the life cycle of construction materials are becoming increasingly sophisticated and integrated within our design practices. These changes impact the characteristics, performance, and integration of our materials and generate creative opportunities to tune design practices that operate with their specificity, embedded complexity, behaviour, and interfaces with fabrication.

In revising and expanding design and construction practice, the need for creativity and resourcefulness becomes paramount. Over the past 14 years, FABRICATE has drawn together a community of exceptional talent, which has demonstrated extraordinary creativity and resourcefulness in tackling emerging issues while articulating the spatial and poetic potentials of fabrication. In this, the latest and fifth edition of FABRICATE, we showcase an impressive range of responses to our call, each of which provides evidence that creative productivity remains wholly intact and targeted towards contemporary challenges with an amplified sense of responsibility and resource consciousness. The fact that this is demonstrated through built and work-in-progress projects indicates a maturing of enriched methodological underpinnings.

In many cases, this work points to the requirement to expand our communities, to enrich our dialogues, and to extend our design boundaries to incorporate knowledge domains previously considered fringe, or even outside of, the architectural project. This is especially evident in the works that articulate relationships between building and regional biomes, and the implications of the scaled use of novel renewable resources on land-use and management. It is also evident in the expansion of our material base with novel material sources and methodologies, specifically within the field of bio-fabrication. In all cases, we see the evidence of our community's creative resourcefulness being provoked towards novel design principles and practices.



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1. Additive manufacture for repair: The shorter life spans of biopolymers create new opportunities for ideating methods of continual construction. In the Eco-Metabolistic Architecture (EMA) project we examine how additive fabrication systems can be embedded into continual fabrication logics to include post-production reparatory actions. © CITA Ruxandra Chiujdea, Paul Nicholas, Konrad Sonne, Carl Eppinger and Mette Ramsgaard Thomsen. The EMA project has received funding from the European Research Council (ERC) under the EU's Horizon 2020 research and innovation programme (Grant Agreement No 101019693).

The curatorial model of FABRICATE asks us to undertake the difficult task of selecting 32 projects that represent the breadth of innovative thinking, technological probing and fabrication-focused design occurring across the sector. With more than 250 paper submissions, representing 400 authors from 32 countries, operating from more than 140 separate worldwide organisations within industry, practice, and academia, FABRICATE 2024 can offer only a glimpse into a much wider shift occurring across the community. This shift is nurturing a plurality of cutting-edge and disruptive models for design and production coupled with a heightened awareness of ecological and social responsibilities.

There are two channels in FABRICATE through which such works are presented and exchanged, the book and the conference, and they are launched in that order. This model, unorthodox in process, in which both channels are mutually and independently structured, timed, and operated, has, since its founding in 2011, become the defining template of the enterprise. This reversal of the typical conference format was envisaged to facilitate and document novel excellence in the fields of academia, practice, and industry, and, upon sharing this material, to stimulate fresh dialogue in momentum. Those familiar with the format will know that the physical book, of which only a small number are printed, is published the night before the conference opens, followed by the distribution of the free open access download a few days later. To date, more than 300,000 copies of the digital version have been dispensed from the UCL Press repository, across more than 185 countries. It is also well known that the call for work does not constrain submissions to a narrow theme. In essence, the triennial call asks its audience to tell us about the most innovative projects they are making, no matter how big or small.

It is a call to share practice-based research from wherever it originates, offering a platform for those operating at the workbench or onsite to speak of their experiences. It seeks to work across conventions, such as the freedom academia enjoys to demonstrate knowledge exchange, set against the restriction this concept has for industry operating in competitive markets. In this sense, FABRICATE taps into vital seams of intellectual generosity in a spirit of fellowship and collaboration that the world urgently requires. The project was launched in 2011 at a time when its convenors had no expectation that it would be anything more than a one-off event. Yet, it has become a uniquely flexible platform for diverse interdisciplinary and pioneering teams whose enduring and evolving works-in-progress informs peer reviewers and editors about the themes that bind them together in context and in time.

In FABRICATE 2011: MAKING DIGITAL ARCHITECTURE, themes emerged as Machines & The Bespoke, Material Systems, Physical Processes, Representation & Manufacture. In FABRICATE 2014: NEGOTIATING DESIGN AND MAKING, they became Challenging Thresholds, Forming Machines, Living Assemblies, Material Exuberance. In FABRICATE 2017: RETHINKING DESIGN AND CONSTRUCTION, they became Rethinking Additive Strategies, Rethinking Constructional Logistics, Rethinking Materialisation, Rethinking Production Futures. Finally, in FABRICATE 2020: MAKING RESILIENT ARCHITECTURE, they emerged as Bio-Materiality, Optimisation for a Changing World, Polemical Performative Practice, Synthesising Design and Production. And now, FABRICATE 2024: CREATING RESOURCEFUL FUTURES is subtitled and structured around trajectories of enquiry identified from this edition's selected contributions. Themes, defined before the subtitle, are not siloes, but interconnected and overlapping domains through which to articulate emerging questions and practices.

Reclaim – Circularity and Reuse asks how practices of resource reclamation can be imagined and what their implications are for design and fabrication across processes of identification, registration, extraction, and reintroduction into the design cycle. They challenge us to suggest new continuity between finite and renewable sources, to query how building-mass designed for short lifespans can be reclaimed, how traditional structural systems can be appropriated for material reclamation, and how computational design methods can facilitate the integration of non-traditional resource strands into the built environment.

Localise – Sourcing and Performance positions resource origin as a critical question for future practice. Over the last 200 years, globalisation has performed the greatest relocation of resources ever enacted. New practices seek deeper relationships with local resource origins through tuning practice to local ecologies, by interfacing with rhythms of resource availability, and by creating practices of novel renewable cultivation, locally integrated into expanded cycles of design to production.

Integrate – Systems and Contexts asks how emergent resource conscious methods of fabrication that optimise material utilisation and systems that are finely tuned to their local environment can be intelligently interfaced with existing building systems. It asks what the ideal convergence between the mass fabricated and the bespoke can be and how strategically rethinking selected building components can reconfigure relationships between old and new.

Rationalise – Elements and Assemblies considers how rationalised whole and part relationships can be brokered through the application of advanced computational design at the intersection of assembly logics and material performance. Through the encoding of rationalised structural and assembly logics, complex geometries are computed, detailed, and fabricated with an acute sense of material use and re-use, whether drawn from finite or renewable resources.

The discourses existing across these four domains are complemented through four Dialogues, each pairing present and past FABRICATE keynote speakers in conversation. This form of presentation offers a continuous thread that arcs through each of the five FABRICATE books.

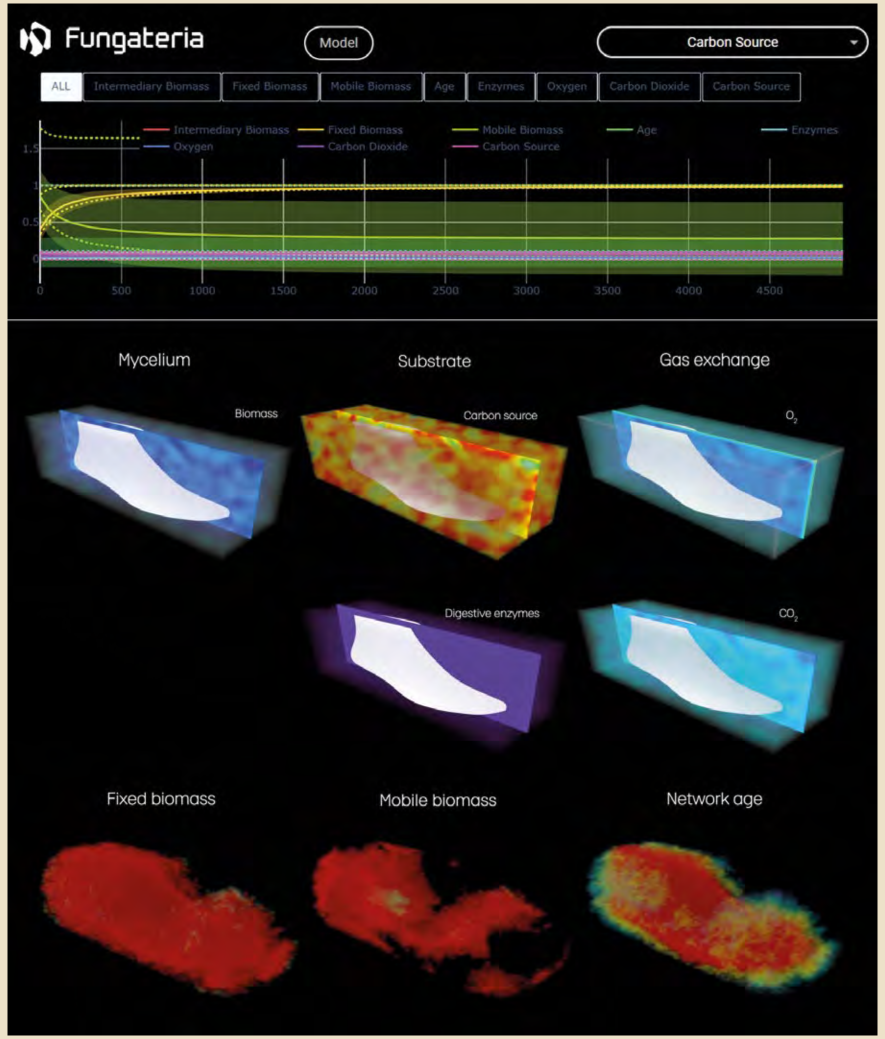
In 2024, Anders Lendager and Meejin Yoon debate the emergence of near forensic design practices that examine the provenance, composition, lifespan, and impact of materials with a horizon towards creative reuse. They ask how this interrogative practice can translate into new business models for architecture in which the continuum between design and fabrication, so fundamental to the FABRICATE community, is retained but also transformed.

Anna Dyson and Kai Strehlke examine novel ecological vocabularies that re-address the way we understand the entangled interactions between resource, energy, and ecology. These vocabularies challenge us to understand how the boundaries of our design system can be reconsidered to learn from and integrate into the ecosystems in which we live.

Indy Johar and Philippe Block discuss the systemic changes that are necessary to achieve carbon neutrality in the built environment, and the need for nuanced and intersectional discourse to prevent siloed and fragmentary responses. Key lever points include optimising the utilisation of buildings and tackling historically grown redundancies in our material fabrics.

In the fourth Dialogue, Zhu Pei and Cristiano Ceccato discuss the importance of operating with local knowledge throughout design and procurement, supported by a spectrum of low and high technologies, with the aim of emphasising the cultural heritage values of material and craft. Here, issues of localisation, material reclamation, and automation combine objectives of optimisation and conservation to create connections and resonances with local fabrication and broader cultural frameworks.

Creating Resourceful Futures
Presented with the task of defining a summary of FABRICATE 2024's entire oeuvre in a subtitle, the solution emerged after prolonged discussion among all four editors, each striving to converge on the proper words to represent and respect such extraordinary, urgent, and important work. Across all papers, including those that were not selected, loud and eloquent concerns for humanities' future prospects were urged on by a firm and optimistic commitment for all of us in positions of choice, influence, power, and privilege, to direct our creative resources responsibly and collectively. In this regard, FABRICATE carries on as a collection of works in progress, now catalogued through 160 projects in 14 years, from more than 500 inspiring contributors, each making a valuable contribution to how we make well.



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2. Modelling of Engineered Living Materials (ELM): ELMs represent a novel class of materials that exhibit living properties. The ability to model their metabolism, morphogenesis and functions is an essential step towards articulating their architectural potential. A minimal viable model has been developed to interrogate the space of growth and parameters for steering properties of the grown material towards architectural objectives. © FUNGATERIA/Chair for Biohybrid Architecture (Vilhelm Carlström, Adrien Rigobello, Claudia Colmo, Ji You-Wen, Amaya Steensma Tedder and Phil Ayres). FUNGATERIA under the EU's Horizon 2021 research and innovation programme (Grant Agreement No 101071145).

Finally, we would like to conclude by expressing our mutual honour that FABRICATE 2024 is being held at The Royal Danish Academy: Architecture, Design, Conservation, where two key centres are located. Since its first iteration at The Bartlett School of Architecture, UCL, in 2011, followed by its move to ETH Zürich in 2014, the University of Stuttgart in 2017, and online via Cornell University and Swinbourne University of Technology in 2020, each host has been elected in recognition of its record of contribution, excellence, leadership, and influence. The 2024 host, CITA (Centre for IT and Architecture), is no exception. Established at the Royal Danish Academy for more than 20 years, and led by Professor Mette Ramsgaard Thomsen, CITA is a world-renowned research centre investigating how computational logics and associated technologies for automation, fabrication, and modelling drives new questions about what architecture can be. CITA's key effort lies in contextualising technologically led architectural explorations that are both rigorous scientific enquiries and conceptually probing. The aim is to understand architecture as fundamentally technologically informed while at the same time positioning and reinforcing our critical and creative traditions as a method for knowledge creation.

Working alongside Ramsgaard Thomsen within CITA for the past 14 years, Professor Phil Ayres has recently established the Chair in Biohybrid Architecture – the first of its kind in Denmark. The objective of the Chair is to cultivate the budding research field that combines living organisms with digital and technical components. The field focuses on incorporating the characteristics and dynamism of living complexes – such as growth, self-repair, decision-making, and resource balancing – creating opportunities to invent novel spatial and tectonic vocabularies, architectural technologies, and widening architectural theory and practice. Research at the Chair for Biohybrid Architecture focuses on entwining computation with deeply rooted technologies such as weaving and fermentation – recognising each as deep reservoirs of innovative potential and benefitting from being pan-culturally anchored and adaptable to local resources. This research has been pursued in the context of the EU funded projects Flora Robotica, Fungal Architectures, and Fungateria.

Welcome to FABRICATE 2024. Welcome to Creating Resourceful Futures.

LOCALISE
RECLAIM
INTEGRATE
RATIONALISE

1

LOCALISE

SOURCING AND PERFORMANCE

FORAGING FOR A FIELD STATION
CULTIVATING MATERIAL EFFICIENCY

EMMANUEL VERCRUYSSE / KATE DAVIES / WYATT ARMSTRONG
ARCHITECTURAL ASSOCIATION

Introduction

Within industrial timber production, it is widely accepted that as little as 50% of a standing tree makes it into a building component. This is partly an outcome of the process of harvesting, where the crown timber and branches are left behind in the forest.

This project deploys an innovative robotic application to enable the use of this foraged small-diameter roundwood (50-90mm, usually a by-product of timber harvesting) as the primary building component in a 100m2 roof system for a field station at Hooke Park in Dorset, UK. The application for this zero-value timber promotes a radical rethinking of the timber supply chain and a strategic repositioning of advanced technologies within the production of timber architecture.

Carefully nested within the fabric of the industrial woodland at Hooke, the Field Station is a flexible-use shelter – providing a field base for research and teaching, shelter for our forester and for passing walkers, and an outdoor classroom for local forest schools, as well as being a base for informal gatherings, talks, and events on site (Fig. 2). In the longer term, the Field Station is imagined as an observatory for monitoring change, as the neighbouring agricultural landscapes in view from the Field Station undergo a rewilding programme and as the forestry growth and harvesting evolve around it.

The project resulted in a lightweight and demountable roof frame structure that is assembled without the use of permanent mechanical or glue fixings. Designed for disassembly, the roof structure comprises two planes of chords that are held together by threaded rod, which forces all the diagonal roundwood branches into compression allowing the use of straightforward tenon connections.

A forest context

Hooke Park is the Dorset campus of the Architecture Association (AA). Set within its own working woodland, it is a laboratory for large-scale experiments in timber architecture and for research that places the forest at the centre of the work. Because Hooke Park processes its own timber and manages the woodland that supplies it, the academic and research programmes based there are uniquely positioned to interrogate and innovate across the timber supply chain, from sapling to building.

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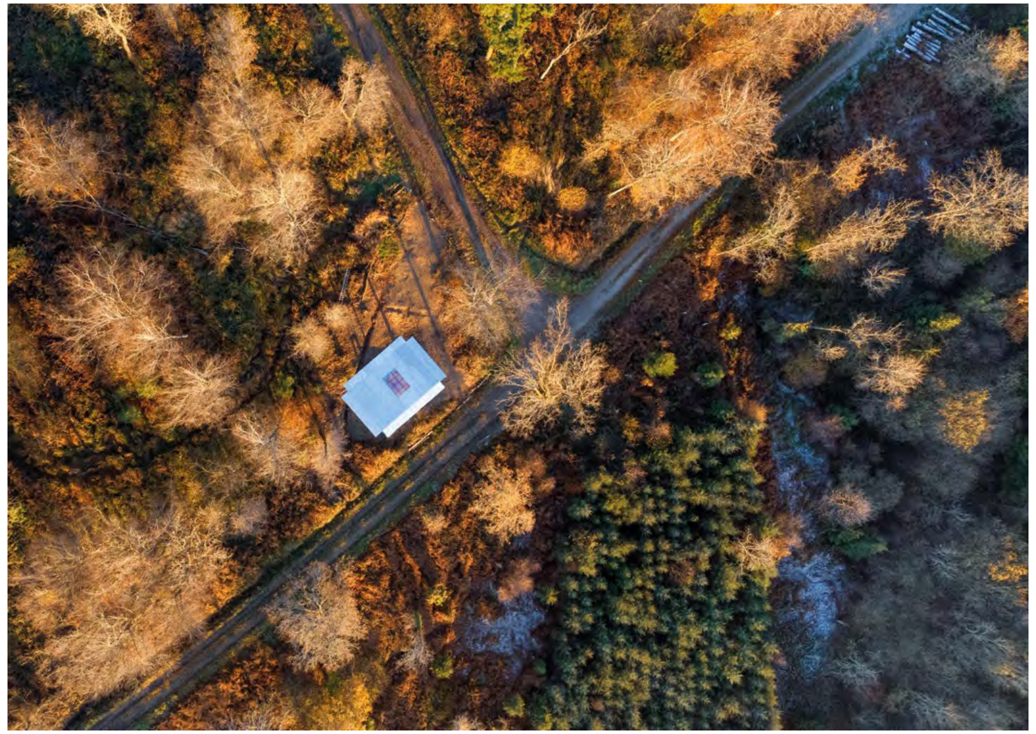
Situated apart from other campus buildings, and set within the working forest, the Field Station is a 100m² open air structure designed and built by students and staff from the AA's Design + Make postgraduate programme. (Fig. 1). The challenge was to devise an architectural application for 'forestry waste' crown timber – small-diameter roundwood of limited market value, commonly left on the forest floor as a by-product of the harvesting process – and to demonstrate how an undervalued resource might be transformed into valuable construction material.

The material parameters for the built demonstrators are in many ways defined by the silvicultural approaches and woodland management strategies of the past. Decision-making in forestry can be measured in decades if not centuries, and the project is envisaged as a space for students, researchers, and ecologists, as well as our forester, to work 'in the field' as they engage with the long-term thinking necessary for the development of future forest strategies for a climate-resilient, healthy woodland. Forest plantations for timber are not merely crops: they are complex ecosystems, increasingly understood as *intelligent* systems and akin to human societies, being complex, adaptive, and self-organising (Simard, 2021).

The Field Station uses two species of timber – Beech and Ash – both of which are at risk. Beech is among the leading British tree species considered most at threat from climate change (Hemery *et al.*, 2021, p.201), while Ash is under siege by a fungus that leads to dieback. Both tree species were harvested at Hooke in 2021 as part of the woodland management plan, and both provide material for the build. The forest residue – after the industrial harvester has passed through the Beech section – is made up of 50-90mm-diameter branch timber, which forms the primary building material deployed in the project. This material accounts for a substantial portion of timber left behind in the forest.

The structural logic was developed together with the engineering team at multinational consultancy Arup, resulting in a space truss that incorporates Beech roundwood braces within a dimensional Ash grid. This facilitates a 3m cantilever on all sides. The integration of a bespoke computer vision system with robotic fabrication ensured the precision of 256 roundwood braces, adapting to natural branch variations.

In this way, a relationship is somewhat inverted: the forest dictates material parameters, and these parameters lead the design, while technological strategies serve to elevate the status of a discarded material for an application of



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zero-value timber, working with what the forest at Hooke Park provides. It suggests an enhanced adaptive, localised approach to material resources.

The option of using small-diameter roundwood thinnings for the linear members was something the team was initially keen to explore. However, it found there was not enough timber of suitable length and diameter available for harvest from the forest at the time. Stitching shorter lengths together was a possibility, although it might well require a slightly different structural approach, and the top and bottom of these members being machined to achieve the accuracy. (The advantage of the double frame-sawn linear members is that they automatically generate the nodal connection.) This investigation simply proved unfeasible within the academic timeframe of the project. Although it was a trade-off, the explicit constraint set to students was to work only with what our forest could provide, and it was also important to hold to this ambition. The Ash used for the sawn-timber grid locating the diagonals, was sourced from our own forest. Since dieback has affected trees in Hooke Forest, some Ash is being harvested early (Figs. 5, 6).

Pursuing a wholly roundwood space-truss construction is a proposition that would be interesting to develop further, as it could be argued that the top and bottom linear

1. As a point of observation, the project engages with, and bears witness to, its immediate surroundings. © Design + Make Postgraduate Programme, Hooke Park.

2. The strategic location of the Field Station, firmly nested within the forest context. © Design + Make Postgraduate Programme, Hooke Park.

3. The industrial harvester at work in a Beech stand at Hooke Park. © Frederik Petersen.

4. The tenons and shoulders on robotically machined small-diameter roundwood. © Design + Make Postgraduate Programme, Hooke Park.

members as machined timber are dominant, and might feel counter to the objectives of the project. Yet there is something unexpected in the aesthetic contrast within the structure; the clean lines of the sawn timber are striking when seen alongside the natural branch forms, and perhaps this tells its own story.

The brief for the Field Station required that it touched the earth lightly, and that it was temporary and demountable, exemplifying principles of flexibility, reuse, and future reclamation, in keeping with ideas of the circular economy. The lack of permanent mechanical fasteners or glue, using only central tensioning rods at each node, which can be easily removed, facilitates demounting. The components were fabricated, flat-packed, and transported on site for a swift assembly process, completed in just ten days (Figs. 11, 12, 13, 14). This flexibility offers a dynamic shelter within an evolving working forest. The Field Station's mobility offers the potential for relatively simple relocation, capable of adjusting to the woodland's periodic thinning and felling over time. In its present position it faces south, framing a changing landscape – oriented towards a spruce compartment felled and replanted five years ago, and looking out towards the neighbouring Mapperton Estate, which is in the midst of a large-scale rewilding project. It serves as an observatory, a teaching space, a shelter for the forester, a base for researchers and ecologists measuring soil health, counting moths and bats, a resting point for walkers. It is a space for witnessing and monitoring change in the landscape over extended periods of time.

Crown timber, which is typically discarded as waste in contemporary forestry operations, is the key component and research focus for the project. Depending on the type and age of the tree, this material may account for 20-50% of its overall above-ground biomass. A 2015 global tree study (Crowther *et al.*, 2015) concluded that at that time Canada had 8953 trees per person, the US 716, France 182, and the UK just 47 trees per person. Given that in tree terms the UK is one of the poorest nations in the world, with woodland cover comprising only 13% of the country's total land area (Forest Research, 2023), it seems important to use as much as possible of a harvested tree, and for designers to create use cases towards this goal. By using branch wood braces rather than traditional dimensional lumber, the amount of timber saved was equivalent to two mature Beech trees. In a nation with little forest cover, this method significantly reduces the material waste of harvested trees from 50% to 10% (Fig. 3).

To forage the material for the build, students spent many hours searching the forest floor for Beech branches that met the project's requirements for size and quality – a form of visual grading. This is reminiscent of earlier foraging traditions known as *estover*, a term that refers to an allowance of wood that a person can take from a commons, and derives from the French *estovoir*, meaning *that which is necessary* (Fig. 4).

This project fits into a broader context within the Design + Make postgraduate programme at Hooke Park, which looks at minimally processed timber and aligns with a lineage of research established at Hooke Park in the 1980s by John Makepeace, Frei Otto, and Adrens Burton Koralek, which involved testing the structural applications of forestry by-products through constructing buildings on site. Over the past eight years, a series of projects – Boiler House, Woodland Cabin, and Woodchip Barn (Self and Vercruysse, 2017) – have explored the unique structural geometries of trees, starting at the ground, and now, with the Field Station, working up into the crown. Other projects at Hooke Park, such as the Foundry (Vercruysse *et al.*, 2019) and the library skeleton (Vercruysse, 2020a), have advanced the scope of robotic workflows in the built work (Vercruysse, 2020b). The innovation in the Field Station – and the departure from robotic workflows used on past projects – lies in the integration of the bespoke vision system.

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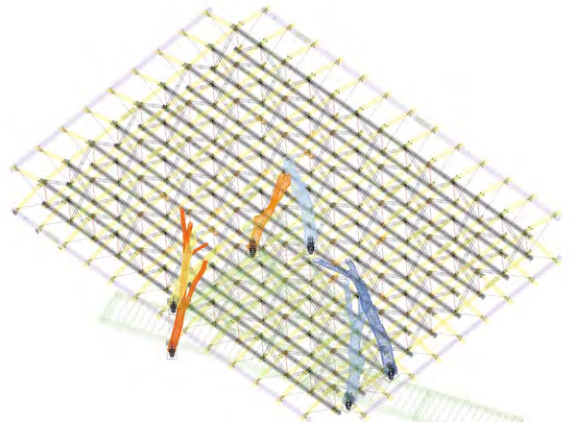

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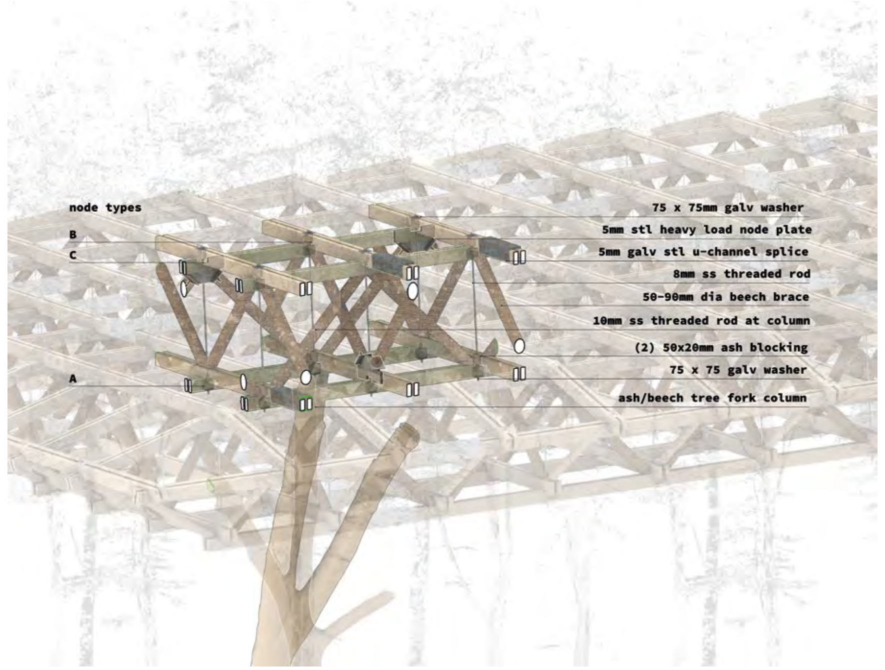

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A vision system

By integrating a vision system within the Hooke Park robotics cell, crown timber branches can be processed into precise, predictable geometries, accounting for natural variation in an element's geometry. With every web element in the space-frame system having its own unique shape at the time of harvest, an automated workflow comprised of scanning, part analysis, and toolpath generation enabled an efficient production of structural components, processed into connection details only where the branch meets the building.

The guiding framework for this robotic setup was the delivery of 256 identical components from non-standard timber. The ambition was to build a robotic application to process leftover Beech crown timber into high-quality structural products. Within the design of the Field Station, the elements made from these branches fit into the building's structural system by the geometry defined at their extremities. However, there are no geometric conflicts with any other elements along their length. By integrating a vision system with an indexing circular saw, non-uniform geometries could receive a series of targeted cuts at their ends, extracting a pair of in-plane tenon joints from the branch volume.

This application for robotic vision is enabled by an Ensenso N30 structured light scanner, typically used in factory settings for quality inspection or bin picking. This 3D camera is equipped with two cameras trained inwards to produce a rough sense of binocular vision. This provides a good sense of lateral positioning, but a poor understanding of depth. The camera's depth perception is snapped into focus by a projector placed between the two camera lenses. When firing, the projector emits a bright pattern of blue light that resembles a fine-grain QR code. The camera's internal computer compares a scaled flat version of this pattern with the one it now sees wrapped across an object's geometry and measures its deformation across the object's surface. This brings the camera's depth accuracy to ±0.5mm. Parts are brought to a distance of ~500mm from the camera to sit within its focal length.

The vision system is one of several additions to the robotics cell that enabled this project. Opposite the 3D camera is a Union Graduate cast steel bowl lathe. In this application the lathe was used to index a cutting blade to allow for greater flexibility in cut positioning. The camera and the lathe flank the robot on either side with roughly 4m between them. In front of the robot is a rail system that is hung from the outer wall of the cell. The rails are loaded with branches from outside the cell so the robot can be kept 'fed' without the safety perimeter of the cell being broken. A small opening was made in the front wall of the cell with a slide protruding through to allow the finished branch components to exit the cell and be collected. As essential as the vision system is the cutting tool.

5. Global diagram illustrating the transition of the forces from the roof structure via the tree column to ground. © Francis Archer, ARUP.

6. Highlighted section of the structural system through the Field Station. © Garrett Nelli, Design + Make Postgraduate Programme 2021/2022.

7. Robotic gripper and feed station of the branches in their raw state. © Will Gowland.

8. Robotic scanning of individual branch geometry. © Will Gowland.

9. Production of the repeated branch component of the spaceframe through the use of the indexed circular saw. © Will Gowland.

10. Exposing the scanning process to resolve the geometric variety of branch components. © Wyatt Armstrong.

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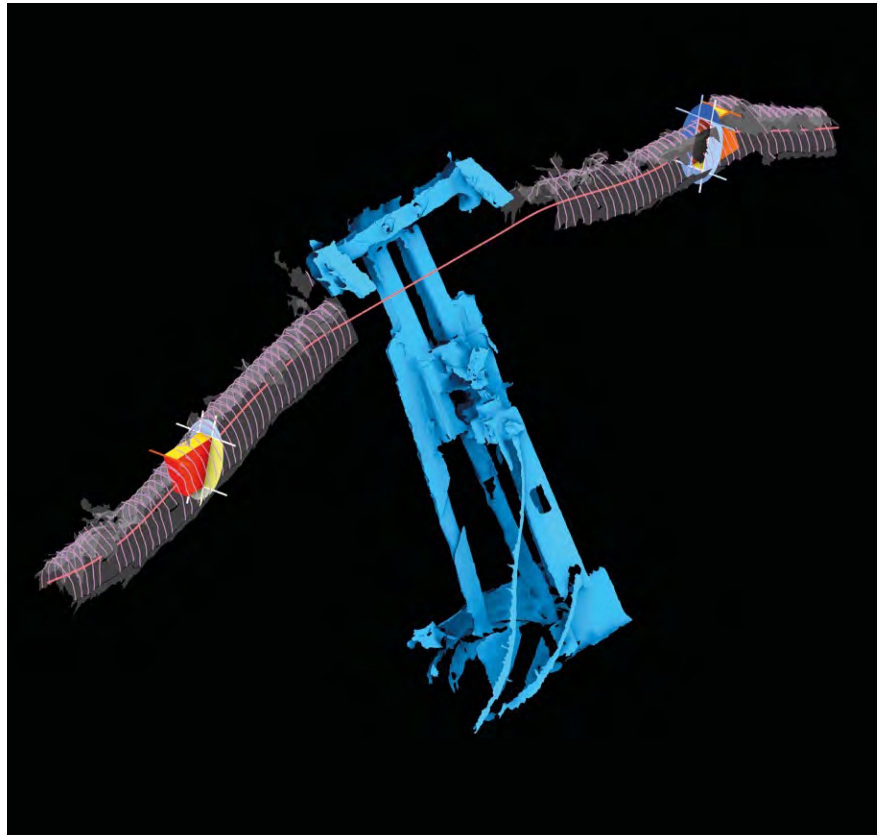

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As branch diameters grew larger through the project, a spindle mounted in a cast steel housing with a 400mm-diameter blade replaced the earlier Makita saw. To carry the branches, the robot is equipped with an in-house-made pneumatic gripper that went through multiple iterations, adapting to increasing branch sizes across the span of the project (Figs. 7, 8, 9).

Using several scripts written in Python and C#, the camera is calibrated and accessed through the environment of a built-in Robot Operating System (ROS). Within the cell, the camera is mounted statically and positionally referenced to the robot's root point. By knowing the camera's coordinate system as an offset from the robot's root point, scans of objects that the robot presents to the camera can be oriented and stitched together by reading the tool control point data at the position from which a scan is taken (Fig. 10).

While the camera is accessed by ROS, requests for the camera to fire are sent form Grasshopper through COMPAS, an open-source computational framework developed by COMPAS Association for Multi-Disciplinary Research in Architecture, Engineering, Fabrication, and Construction. The COMPAS plugin for Grasshopper provides a networked link between ROS topics and information in Grasshopper. Once fired, a point cloud is delivered from the camera to ROS. It is then meshed within ROS and sent over the network to Grasshopper with a timestamp.

Once in Grasshopper, the meshes are linked through their timestamps and compiled into branches composed of four separate scans. The four scans allow roughly three-quarters of the geometry at the branch ends to be documented. Through a contour analysis, the backside of the branch can be estimated by best-fit circles generated by three points on the contours. From the estimated circles, a centreline down the branch is found, to which the modelled geometry of a standardised component can be oriented. In orienting joinery to the branch centrelines, several stages of checks are in place to ensure key geometry of the tenon joints are fully located inside the branch. These involve projecting points on the tenon from the initial orientation back to the branch scan and adjusting accordingly.

The robotics toolpaths are derived from the planes and cut edges of the modelled joinery. Once the modelled joinery is verified to be within the scanned branch, the robotic movements are automatically updated. The motion planning involves matching the planes and defined edges of the tenon joints to several planes located on the circular saw. There are 11 surfaces that define the two tenons at either side of the branch. To prevent the robot's axes from reaching high rotational values, the indexing of the saw blade allows the robot to make cuts perpendicular to each other without much change in position.

The robotic application for the Field Station nests into the academic work of other institutions exploring the analysis of timber through scanning technologies and the robotic fabrication of complex trussed structures. The work of the Field Station has parallels with the Timber Stories project (Svilans *et al.*, 2022), presented at the Works+Words 2022 biennale in Copenhagen, in the analysis of the internal structures of timber through CT scanning for optimised milling layouts. Also analogous is the work at ETH with Gramazio Kohler on House 41781 (Gramazio Kohler Research, 2016), in which the cutting and assembly of standardised timber elements within a spatial trussed assembly was automated. Occupying a territory between these projects, the Field Station does not seek to fully automate the production and assembly of the truss, or to fully comprehend the precise geometry of the pith and branches within the timber, as the continuity of grain is not being severed along the element's length. Instead, it pushes a middle ground between these projects that leverages the inherent strength of round timber and elevates the connection details of what would otherwise be considered a waste product, to furniture-grade levels of craft.

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11. Layout of the assorted components of the Field Station, flat-packed and ready for deployment on site. © Design + Make Postgraduate Programme, Hooke Park.

12. Roundwood and machined timber stitched together and pretensioned, ready for lifting in place. © Design + Make Postgraduate Programme, Hooke Park.

13. The intricacies of a complex assembly logic. © Design + Make Postgraduate Programme, Hooke Park.

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14. The 4-ton roof structure is airlifted in to place and securely fastened to the Beech tree fork columns. © Design + Make Postgraduate Programme, Hooke Park.

Project credits

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MULTI-SCALAR COMPUTATIONAL FABRICATION AND CONSTRUCTION OF BIO-BASED BUILDING ENVELOPES THE *LIV*MATS BIOMIMETIC SHELL

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Introduction

Architecture, Engineering, and Construction (AEC) industries are increasingly embracing digital fabrication technologies. The trend offers potential for significant benefits, including enhanced resource efficiency, increased productivity, reduced construction waste, and improved worker safety (Agustí-Juan *et al.*, 2019). While digital fabrication research has introduced various tools and methods, their practical adoption in the industry remains limited, especially for fully functional building projects (Graser *et al.*, 2021). In addition to technical challenges, there are organisational and procedural barriers to adopting digital fabrication. Digital fabrication needs to be developed collaboratively, spanning multiple research disciplines and professions (Knippers *et al.*, 2021).

This paper presents the multi-scalar computational fabrication and construction approach used to construct the functionally integrated and bio-based building envelope of the *liv*MatS Biomimetic Shell. The lightweight, long-span timber structure spans 200m^2, featuring 127 interconnected hollow cassettes. Three digital fabrication processes – each with its own resolution, accuracy, and functionality domain – were integrated for the construction of an exceptionally functional building envelope: 1) the robotic prefabrication of high-precision timber building components, 2) the large-scale robotic assembly of these timber building components into a segmented timber shell, and, finally, 3) the millimetre-scale additive manufacturing of cellulose fibres for adaptive façade components.

State of the art

Wood combines environmental and structural advantages with excellent machinability and workability. It therefore offers opportunities for future-proof automated fabrication processes and could lay the foundation for a sustainable revolution in construction technologies. Nevertheless, the timber construction industry at present relies on the use of fully integrated, flexible digital fabrication technologies exclusively for subtractive manufacturing, with limited exploration of the integrative potentials of computationally controlled additive processes. Embracing robotic fabrication to its full potential can expand the possibilities of working with timber. Noteworthy examples include the DFAB House, The Sequential Roof, and the Annen Head Office Project. Another example is the predecessor building of the *liv*MatS Shell – the BUGA Wood Pavilion

1. Exterior view of the *liv*MatS Biomimetic Shell. © ICD/ITKE/IntCDC University of Stuttgart, Roland Halbe.

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– a 30m-spanning roof that is built from robotically assembled wooden cassettes (Alvarez *et al.*, 2019).

Automated construction assembly tasks remain reliant on manual labour. There are significant challenges to address, such as managing unpredictable and unstructured work environments, adapting workspaces and machinery for large-scale projects, and seamlessly integrating building design with automated processes (Leder *et al.*, 2019). The light weight of wooden components means they offer significant advantages for fully digitally controlled and adaptable construction assembly automation within timber construction (Ramage *et al.*, 2017). Nevertheless, this topic is under-explored – especially for non-standard element geometries and the integrated automation of structural joining of components (Opgenorth *et al.*, 2024).

Amidst digital fabrication processes, additive manufacturing of façades has attracted significant attention, primarily due to its advantage in providing geometric freedom, complexity, and material efficiency. A notable advancement in this domain is the emergence of 4D printing, enabling the creation of material systems capable of self-adaptation over time in response to external stimuli (Tibbits, 2014), mirroring the environmentally responsive behaviour observed in hygroscopic motile plants (Speck *et al.*, 2023). Previous endeavours have extended the biomimetic principles of these motile plants to climate-responsive façade systems, achieved through the precise extrusion of hygroscopic, wood-based filaments utilising fused filament fabrication (FFF) techniques (Correa and Menges, 2017). While holding the potential to reduce the energy needed for active heating and cooling, earlier research has confronted feasibility challenges in implementing these applications at an architectural scale.

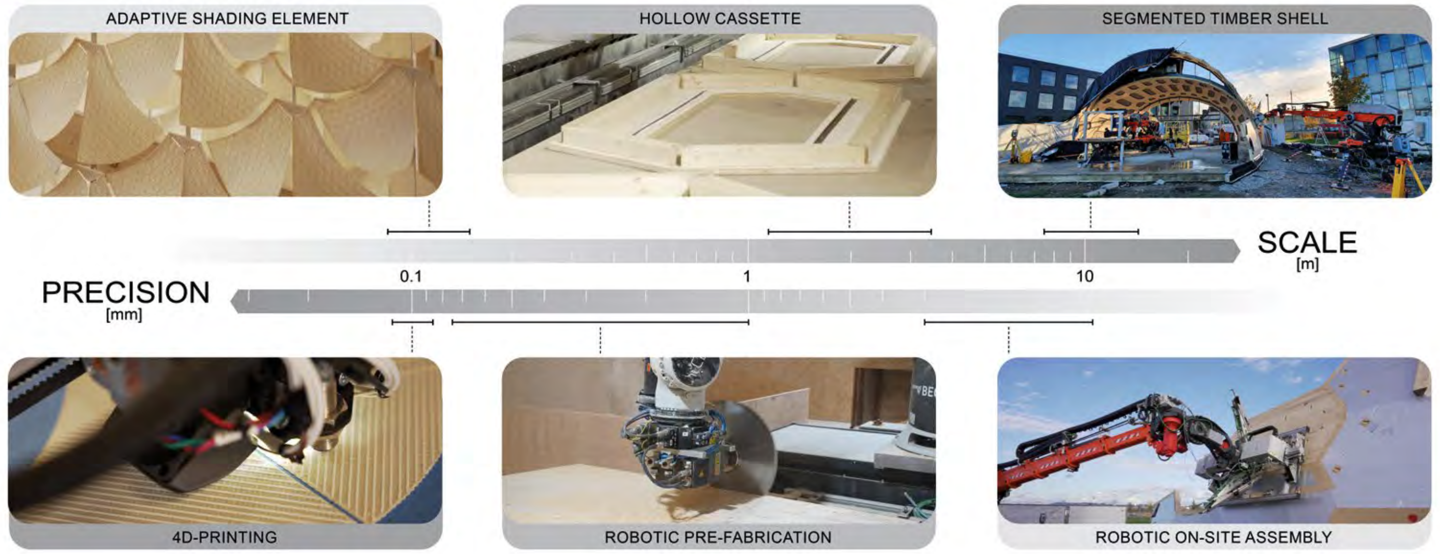
Robotic prefabrication

The load-bearing structure of the *liv*MatS Biomimetic Shell consists of a segmented timber shell, with hollow cassettes that are fabricated using additive and subtractive robotic manufacturing processes. Drawing on features presented in its predecessor project, the BUGA Wood Pavilion (Alvarez *et al.*, 2019), the *liv*MatS Biomimetic Shell showcases enhancements regarding its structurally performative material design, the integration of building functionalities, and the optimisation of software and hardware tools aimed at increasing both fabrication efficiency and cost effectiveness, while maintaining exceptional quality standards.

The upper and lower layers of these hollow cassettes are made from three-ply spruce boards, complemented by solid spruce construction timber beams, significantly reducing the volumes of adhesive and cost compared with the spruce LVL makeup of the BUGA Wood Pavilion. To seamlessly integrate various functions, such as lighting and acoustic features, the cassettes are prefabricated as comprehensive units. To facilitate the automated on-site assembly process, the cassettes feature strategically positioned predrilled pockets that were codesigned with the effector of the spider-crane, enabling digitally ingrained precision during installation. Lastly, the hollow cassettes feature intricate connectors designed to interface with the upper façade, which accommodates

2. Robotically fabricated, bio-based building envelope of the $400m^2$ *liv*MatS Biomimetic Shell, consisting of hollow timber cassettes and a cellulose-based passively adaptive shading system. © ICD/ITKE/IntCDC University of Stuttgart, Roland Halbe.

3. Exterior impression of the *liv*MatS Biomimetic Shell, featuring the integrated lighting inside the hollow cassettes. © ICD/ITKE/IntCDC University of Stuttgart, Roland Halbe.



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4. Outline of the multi-scalar computational fabrication and construction approach across various scales of building of the *liv*MatS Biomimetic Shell. © ICD/ITKE/IntCDC University of Stuttgart.

the 4D-printed shading system, cassettes with integrated façade openings to link with the load-bearing lower façade, and transitional elements involving the fabrication and joining of two individual cassettes.

Like the fabrication process employed for the BUGA Pavilion (Wagner *et al.*, 2020), an adaptable 7-axis robot platform was seamlessly integrated within a few hours into the facilities of the industry partner, Müllerblaustein HolzBauWerke GmbH. The robot unit consists of an industrial robot with a 10.5m-long linear axis mounted on a 40-foot container platform and enables the simultaneous production of four cassettes per job with lengths of up to 3.5m. Material supplies were arranged around the robotic platform. This included dedicated stations, such as a mobile plate cart, a beam table, and a 12m work table for concurrent work on multiple cassettes. A mobile cassette cart was deployed to store and transport finished elements, ensuring easy material access and smooth cassette movement, comprehensively improving overall productivity in the fabrication process.

All cassettes were assembled and glued from pre-formatted timber parts and subsequently milled, drilled, and, finally, formatted with sub-millimetre accuracy by means of a large saw blade attached to the industrial robot arm. The relevant data for each fabrication step was stored within a task-data schema and generated from within the computational design environment. The task-data schema creates a shared interface between design and fabrication models. The framework offers a modular fabrication data structure and service-oriented software architecture and has the potential to be independent of the specific building system in use (Skoury *et al.*, 2022). Communication between the main server, the robotic platform, and the workers utilises the Ethernet KRL protocol, composed of a robot client, XML data schema, and the main KRL programme. The accurate task distribution in one shared digital process chain allowed for a flexible, user-friendly, and time-efficient production of complex, integrative cassettes with extremely high precision requirements.

The integration of a human-in-the-loop system allowed workers to execute dexterous tasks in the robotic assembly, while ensuring both safety and a streamlined process flow. This worker-oriented system first processes information from the fabrication framework, then considers the available team of humans and their tasks, and distributes the appropriate in-situ visualisations through head-mounted augmented reality (AR; Yang *et al.*, 2022). Both robotic fabrication and human workers are instructed using the same task–data schema, which enables fluid switching and sharing of tasks all integrated through a central fabrication management system.

Automated on-site assembly

The automated on-site assembly process represents a seamless continuation of digital fabrication, tailored to operate also in the less structured environment of the building site. It begins with the automatic data extraction from the BIM model of the building and extends to the path planning, trajectory generation, feedback control algorithm, and hardware development. With the vision of a fully automated on-site assembly process, this research covers the entire workflow (Lauer *et al.*, 2023).

For manipulating high-payload, real-scale timber components, two large-scale assembly manipulators with end-effectors are developed. The hydraulic boom stems from the Jekko SPX532 mini crane. In order to reach all target poses, the boom is extended by three rotational electric axes. Moreover, to enhance the precision, additional sensors with higher accuracy and resolution are incorporated for every degree of freedom. All measurements and actuation signals are processed by a central control unit.

A novel assembly process has been devised for the building system. The pick-and-place task is performed by the first large-scale manipulator equipped with a vacuum gripper. The cassette is positioned on a pick-up table and aligned with the mechanical stop. The precise positioning of the table is determined using a robotic total station network (RTS-N) and is further facilitated by a distance sensor. For the connecting task, a novel screwing effector is developed. While the first manipulator holds the cassette, the second manipulator positions the screwing effector. The screwing effector has four pins that attach to premilled pockets on the cassettes and pull together to align the main axis with the edge to be connected. Then, the two screwing units are accurately moved along the main axis to the designated predrilled screwing positions for cross screwing. Once the connection of one edge is complete, the frame disengages, and the screwing effector is relocated to the next edge.

For an automated on-site assembly of the timber cassettes, the start poses of the manipulators need to be defined. For that, a reachability analysis is performed to optimise the positioning of the manipulators, maximising the number of reachable assembly poses and minimising the number of repositions. The manipulators are positioned accordingly within the construction site and each pose is measured. To determine the target poses, the collision meshes, gripping, and assembly poses are automatically extracted from the computational building model. Then, Rapidly Exploring Random Trees (RRTs) generate paths from the start to the assembly poses.

For these paths, the trajectory and feedback control algorithm generate the joint velocities for the manipulator. The end-effector orientation is estimated with a Kalman filter. Both end-effectors are equipped with a reflector. Both reflectors are tracked by the RTS-N, which provides the absolute position feedback to the control units of the manipulators in real time. The pose error is transformed into a target-velocity vector. An optimisation problem that minimises the error between desired and current velocity while imposing joint, task space, and hydraulic constraints, provides in each time step the joint velocities to track the target velocity. After synchronising the electric axes and the hydraulic axes, which are subjected to dead times, the hydraulic system can be controlled by a feedforward control combined with a PID controller. In total, three distinct cassettes were robotically assembled – one of them twice – and remain as an integral part of the building.

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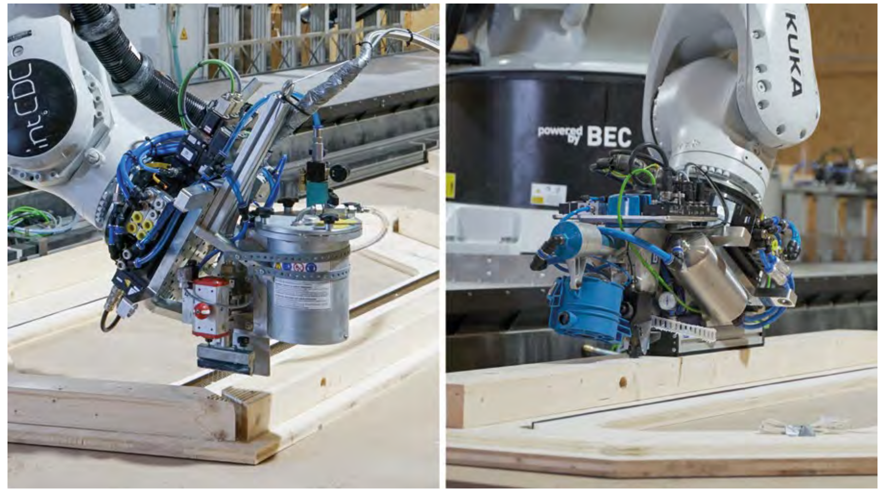

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5. Robotic prefabrication setup for the load-bearing structure of the *liv*MatS Biomimetic Shell, consisting of a 7-axis, 12m-long robotic platform fabricating four hollow cassettes in parallel. © ICD/ITKE/IntCDC University of Stuttgart.

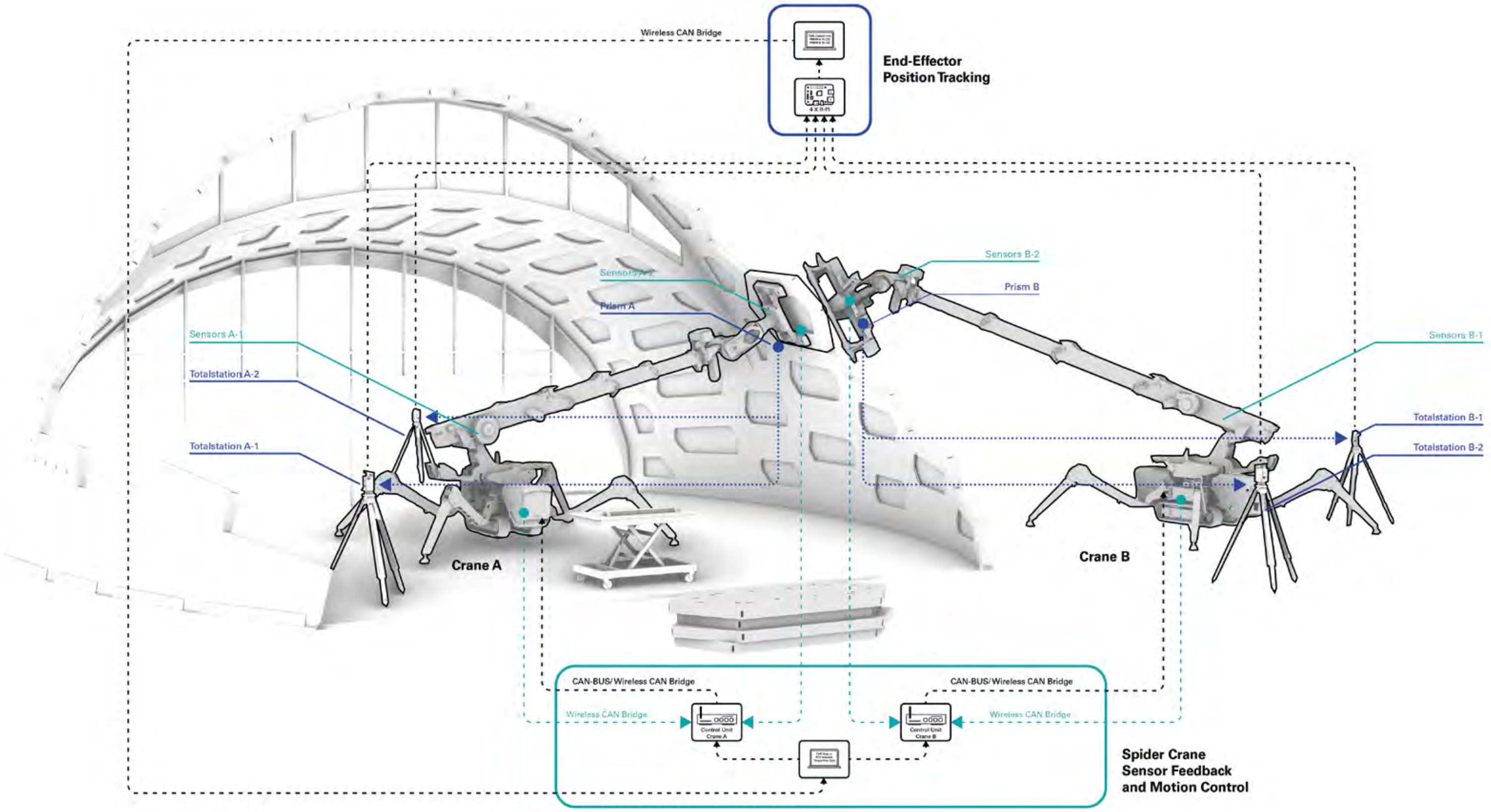
6. Robotic prefabrication assembly process of the *liv*MatS Biomimetic Shell. A total of 127 individual hollow cassettes were glued (left) and assembled (right) together. The cassettes include embedded acoustic elements, lighting fixtures, and integrated insulation. © ICD/ITKE/IntCDC University of Stuttgart.

7. Using a 650mm saw blade, the cassettes are cut to their final shape with millimetre precision. Further grip holes for on-site assembly, screw-pockets for on-site connection, and façade interfaces are integrated through additional robotic milling processes. © ICD/ITKE/IntCDC University of Stuttgart.

8. Human–robot collaboration enabled workers to safely perform precise tasks during the robotic assembly. AR headsets were used to provide real-time instructions and safety information, allowing two workers to install electronics in cassettes simultaneously, while the robot executed its tasks in parallel. © ICD/ITKE/IntCDC University of Stuttgart.

4D printing for a passively adaptive shading system

Situated in the upper façade of the *liv*MatS Biomimetic Shell, a passively adaptive 4D-printed shading system, combined with a low temperature activated slab made of recycled concrete, assists in providing year-round indoor comfort with minimal building services. The adaptive shading system is composed of 4D-printed hygroscopic elements that change their shape in response to fluctuations in the relative humidity in naturally occurring daily and seasonal weather cycles. Through their shape-change, the 4D-printed elements provide adaptive shading that allows solar gains to be captured during winter, while at the same time shielding the building's interior from high heat loads in the summer months.



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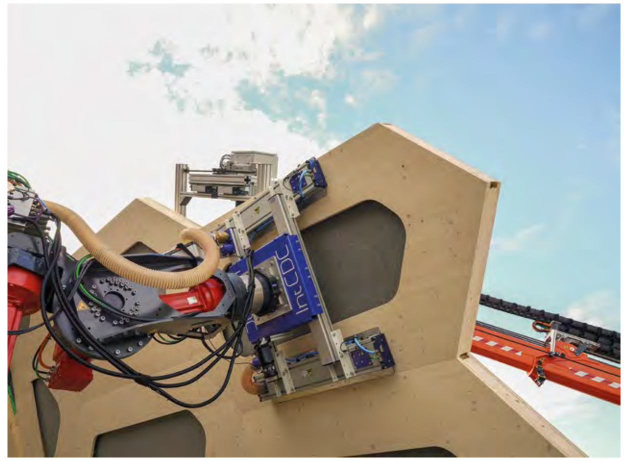
9. Diagram summary of the robotic on-site assembly process of the *liv*MatS Biomimetic Shell. Robotic total stations provide real-time measurements of absolute positions, ensuring accuracy within a few centimetres through trajectory generation and feedback control. © ICD/ITKE/IntCDC University of Stuttgart.

The self-shaping shading elements were 4D-printed using custom-engineered bio-based filament comprising native cellulose powder and partially bio-based thermoplastic polyketone (Kliem *et al.*, 2020; Tahouni *et al.*, 2023). A computational design process was developed for programming the mesostructure and mesoscale arrangement of extruded material paths that dictate the bioinspired self-shaping functionality, which was directly converted into the printing toolpaths and generated GCode (Cheng *et al.*, 2020). In long-term experiments spanning more than a year, the resulting 4D-printed material system was physically evaluated under controlled isolated conditions as well as under real-world weather conditions, validating its performance in terms of responsiveness, durability, and long-term reliability.

The shading functionality of the 4D-printed material system has been designed in the context of environmental and site conditions, accounting for various impacts on aspects such as the geometry and dimensions of the elements as well as fabrication constraints, resulting in a total of 424 unique shading elements. These were 4D printed using four 3D printers (FELIXprinters, IJsselstein, Netherlands) in just 17 working days. The high resolution and sub-millimetre features created from this fabrication process define the performance of the façade on a large scale, as the 4D-printed shading elements adapt to changes in daily and seasonal weather cycles without using any operating energy. Through the integrated development of bio-based, cellulose-based filaments and bio-inspired 4D printing, the approximately $10m^2$ tessellation of self-shaping shading elements have been tuned to respond to the naturally occurring patterns in relative humidity (RH) and temperature in Freiburg, Germany, thereby autonomously opening when triggered by the high RH and correspondingly low temperatures, and closing when triggered by the low RH and correspondingly high temperatures.

Results and discussion

The *liv*MatS Biomimetic Shell presents an approach that aligns with 21st-century requirements of sustainable construction, by leveraging high levels of automation and material efficiency. It encompasses novel planning techniques, building materials, construction methods,



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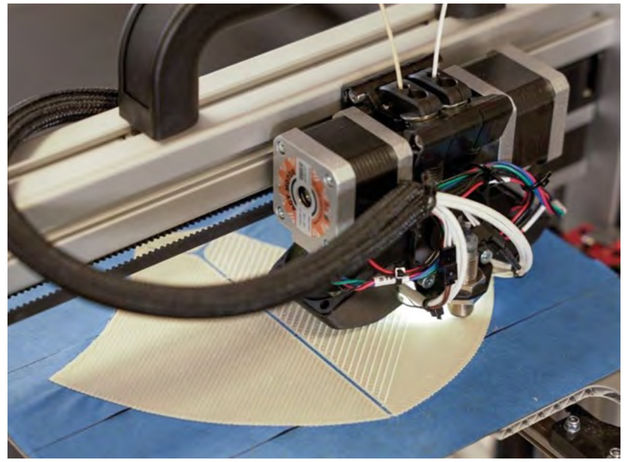

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and systems, along with enhanced work conditions for on and off-site construction. Additionally, it unlocks architectural potential by enabling low-cost mass production of customised components, countering the pervasive standardisation and repetition in contemporary construction practices. When assembled, the curved timber shell serves as a form-active structure, achieving a 16m free span at only $27kg/m^2$. Coupled with the structurally efficient shell design, these cassettes demonstrate how digital technologies can enhance resource efficiency and sustainability in timber construction. The shell is fully deconstructible and reusable, ensuring the separation of all structural components. A comprehensive life cycle analysis (according to ISO 14040–14044 and EN 15804) reveals that the *liv*MatS Biomimetic Shell reduces material consumption by more than 50% and reduces global warming potential by 63% when compared with conventional timber construction.

Robotic prefabrication enabled the precise production of intricate cassettes and facilitated a seamless transition from the digital realm to the physical realm in the fabrication process. Compared with the BUGA Pavilion (Wagner *et al.*, 2020), the robotic fabrication runtime was reduced by 75% through the use of a saw blade, the omission of finger joints, and the implementation of larger hollow cassettes. Future research aims to minimise robot downtime in fabrication processes by enhancing periphery integration for faster material resupply. Additionally, integrating dust collection systems with milling tools and platforms will reduce wood chip accumulation, preventing frequent cleaning and mechanical clogs for uninterrupted operation. A human–machine collaboration procedure was established through AR, coordinating two workers in parallel with the robot. This allowed a further integration of components, especially those that commonly require human dexterity, directly into the prefabrication workflow.

The integration of assembly logic during prefabrication facilitated automated on-site assembly and joining processes using two hydraulically actuated large-scale manipulators, which were successfully implemented on a real construction site. Since the prototypes were tested for the first time on the construction site, the speed limits of the screwing effector and the manipulator joints were not exploited. Instead, a conservative speed was used for the proof-of-concept study. Simulations with speed exploitation indicate that the required time per cassette could be reduced to a third of the time needed by the construction workers if the screwing effector could execute a precise clamping with the necessary force. If not, the required time per cassette could be comparable to the time needed by the construction workers. In the context of a constrained labour market and spiralling building demand, automated on-site assembly robots can boost productivity and efficiency, as they can work 168 hours a week at a constant speed. The study serves as a proof-of-concept that automated on-site assembly of high-payload form-fit timber building elements is feasible and has the potential to benefit construction quality and productivity.

As the first truly weather-responsive 4D-printed building façade, the developed system has proven the feasibility of bio-inspired additive manufacturing and the use of abundant and renewable bio-based materials. Facilitated by the precise material allocation of FFF 3D printing, the economical use of cellulose-based filament underscores the potential of passively adaptive 4D-printed shading systems as an inexpensive, accessible, and energy-autonomous adaptive façade solution. To further enhance

10. Robotic on-site assembly process of the *liv*MatS Biomimetic Shell. Two large-scale manipulators work together to autonomously assemble the prefabricated cassettes. One manipulator is equipped with a vacuum gripper, while the other has a screwing tool. © ICD/ITKE/IntCDC University of Stuttgart.

11. Robotic on-site assembly process of the *liv*MatS Biomimetic Shell. The screwing effector on the manipulator is used to fine-tune the final positioning by utilising the grip holes integrated into the prefabricated cassettes. This allows for adjustments that account for on-site positioning tolerances and ensures a precise millimetre-level connection of the building elements. ©ICD/ITKE/IntCDC University of Stuttgart.

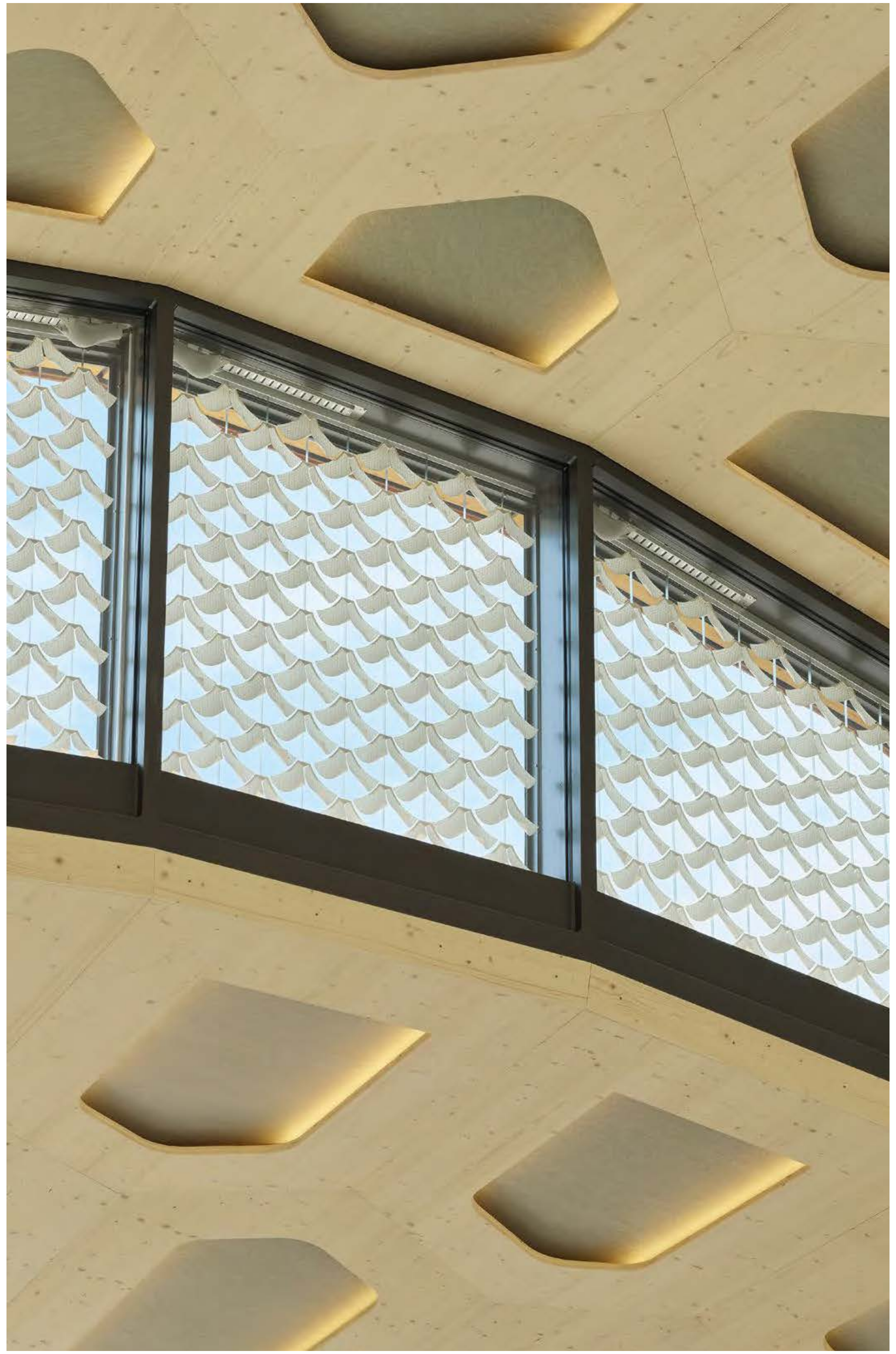
12. Cellulose-based biocomposite materials and high-resolution 4D-printing fabrication process of the self-shaping elements for the *liv*MatS Biomimetic Shell. © ICD/ITKE/IntCDC University of Stuttgart.

the efficacy of the system, there are several key research areas warranting attention. The assembly time of the shading elements can be further optimised by leveraging advanced robotic assembly. The performance of the proposed system can be compared with conventional shading systems by conducting a comprehensive examination of how the developed shading system influences occupant comfort in the long term. This includes precise measurements of the resulting fall in energy usage for climate control. Moreover, automating the override of passive systems in response to unforeseen weather events could expand the application potential of weather-responsive 4D-printed building façades.

The project was conceived with an integrative and interdisciplinary approach to planning and construction, and the goal is to provide a methodological framework for the comprehensive modernisation of construction processes with bio-based materials. It considered various factors, such as building codes, material physics, robotic fabrication, assembly order, low-carbon material systems, structural optimisation, and climate engineering. While this research underscores the potential of co-design and multi-scalar integration in digital architecture, organisational and procedural challenges persist alongside technical hurdles to adopting digital fabrication across all scales within the industry. Although the use of digital tools contributed to streamlined planning and fabrication, the integration of diverse research fields into a single project proved to be a coordination-intensive process. The absence of a common language and shared understanding among team members added complexity. A common and shared paradigm for digital construction across scales and disciplines needs to be further co-developed to address these issues and improve workflow efficiency.

Conclusion

This research presents the co-design of digital fabrication at multiple building process scales and the potential to digitally plan and construct a high-performance building envelope using regenerative bio-based materials. By offering multi-scalar computational fabrication methods that incorporate architectural design, structural performance, weather-responsive engineering, and off- and on-site construction, the *liv*MatS Biomimetic Shell represents a significant advancement towards a sustainable, resource-efficient, computationally conceived, and digitally built environment.



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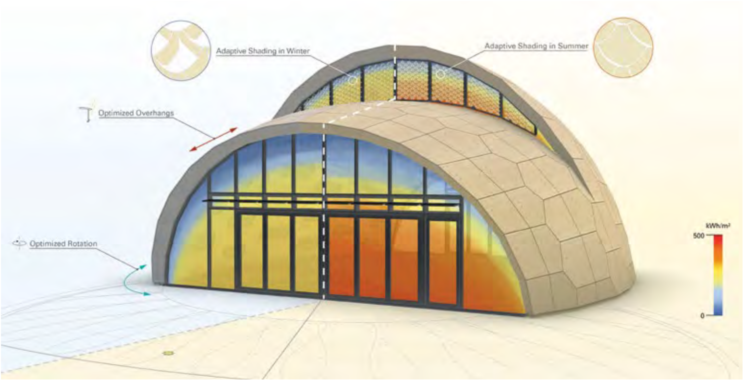

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13. Close-up of the 4D-printed adaptive shading elements in the upper façade of the *liv*MatS Biomimetic Shell. © ICD/ITKE/IntCDC University of Stuttgart, Roland Halbe.

14. Adaptation of the 4D-printed shading system in response to daily weather cycles. The 4D-printed elements close to provide shading during the hot and sunny midday (middle row), while opening up in the early morning hours (top), or at night (bottom) in response to raised relative humidity level. © ICD/ITKE/IntCDC University of Stuttgart.

15. The environmental approach integrates building orientation with 4D-printed adaptive shading elements for year-round optimised heat management. These elements dynamically adapt to weather conditions, providing effective solar control for both daily and seasonal shifts, including east and west angles. © ICD/ITKE/IntCDC University of Stuttgart.

Acknowledgements

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THE LIVING ROOM
NEW EXPRESSIONS OF BIOHYBRID TEXTILE ARCHITECTURE

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How can the intersection of textile practices, biofabrication, and computation disrupt industrial construction processes to deliver scalable solutions for regenerative architecture? Materialised through a textile logic, this research presents a multi-scalar system where the microscale growth of fungal mycelium is structured by permanent knitted textile formwork to support macroscale biofabrication. The outcome is the ability to grow biohybrid textile architecture from a composite of mycelium, wool, sawdust, and cellulose fibres, sourced from local industrial waste streams.

Research context

Transformative thinking is required to achieve net zero in the construction industry. Alternative approaches are essential to both reduce the embodied carbon in building materials, and change the way that buildings operate to minimise carbon emissions during use. The transition to low carbon technologies presents an opportunity to move away from contemporary construction processes and materials. Rather, at this inflection point, the circumstances exist to fundamentally rethink how we design, construct, and inhabit the built environment.

Over the past ten years, there has been a substantial expansion in research focused on biomaterials. In particular, composites biofabricated from mycelium, the root network of fungus, have been identified as a low carbon alternative for future architecture (Elsacker *et al.*, 2020; Jones *et al.*, 2020; Agraviador *et al.*, 2022). To form a composite, mycelium is cultivated on organic substrates such as wheat straw or sawdust, using the cellulose as a source of nutrition. As the mycelium colonises the substrate, hyphae grow and extend to form a three-dimensional network that binds to the substrate materials. After the mycelium is rendered inert through heat treatment or dehydration, a composite material remains. Mycelium grows on a wide variety of cellulose-rich materials, including food waste and agricultural by-products. Conceptually, this presents an opportunity to rethink manufacturing strategies, transforming linear systems into biofabrication ecosystems to repurpose waste from other industries into resources for construction.

While most mycelium composites are formed as blocks and panels using rigid moulds and casting techniques, researchers are developing alternative production systems such as 3D printing (Goidea *et al.*, 2020) and robotic manufacture (Elsacker *et al.*, 2020) to extend the material

properties and geometric complexity achievable with mycelium composites. The Living Textiles Research Group based in the Hub for Biotechnology in the Built Environment is focused on biohybrid strategies that bring together mycelium with textiles, specifically investigating the application of knitted fabrics as a scaffold for growth and a mechanism to transform the look and feel of biotechnologies in the built environment. Previous research by the group developed mycocrete (Kaiser *et al.*, 2023), a formulation of mycelium composite specifically adapted for use with soft textile formwork. Mycocrete combines sawdust, paper fibres, and additives with *Ganoderma lucidum* to form a viscous paste that can be injected into tubular knitted textile formwork.

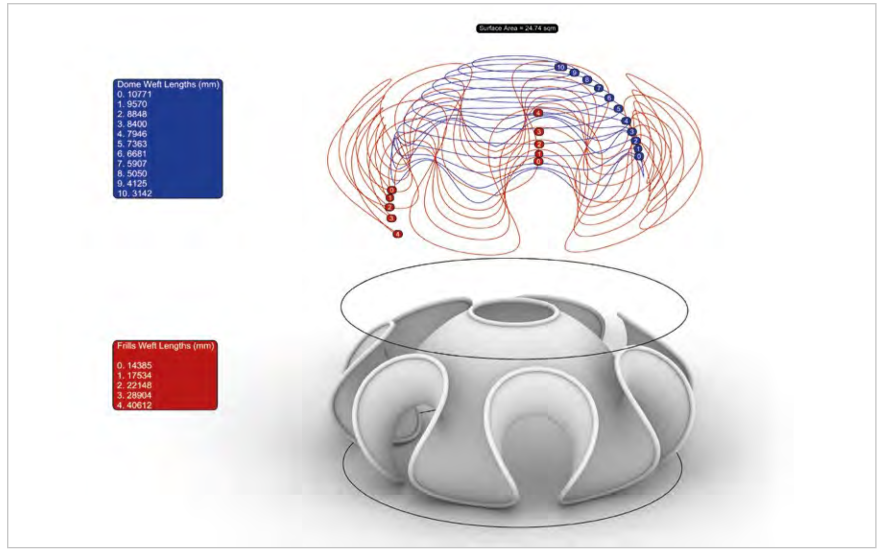
Aims and objectives

The aim of this research is to transform the architectural potential of mycelium composites by developing a knitted biocomposite that achieves new material functionality and a tangible expression of biohybrid textile architecture. Concurrently, the ambition of the research is to set the precedent for transition to 100% waste material for biofabrication, identifying and testing by-products from other industries as resources for mycelium construction. Finally, the approach is to source waste locally, and to tailor a new formulation of mycocrete to the needs of local waste resource.

To achieve this aim, an iterative physico-digital workflow was developed to incorporate multiple research activities. The design strategy moved between parametric modelling and multi-scale material investigation. The resource strategy identified and sourced local waste streams for mycelium composite development. The biofabrication strategy incorporated cycles of growing and material evaluation to determine how to adapt the mycocrete formulation for waste substrates, and how to achieve structural performance of the composite at a large scale. The outcome, *The Living Room*, is a freestanding biohybrid textile architecture reminiscent of a thin-shell vaulted structure. It consists of an exposed knitted formwork on the interior supported by a smooth mycelium plaster on the exterior. *The Living Room* was grown as part of *More with Less: Reimagining Architecture for a Changing World*, the inaugural exhibition at the Farrell Centre, Newcastle-upon-Tyne. It was an interactive installation, which was exhibited to the public for six months in 2023.

Design strategy

The design strategy began with the concept of growing knitted architecture. The research examined how the look, feel, and experience of a space could change if it was biofabricated from wool and mycelium. The form of *The Living Room* was based on a technical exploration of the ability for knitting to form hyperbolic shapes using generative patterns of stitches. At a small scale, knitted models created by systematically increasing the number of stitches over multiple courses produce self-supporting 3D forms. As the amount of material increases within a flexible, continuous surface, the surface is forced to deform out-of-plane; this gives knitted fabric the unique ability to be easily shaped into complex doubly curved geometries. The design strategy was to use parametric modelling, and unconventional freehand knitting techniques, to scale up this technique to the size of a room.



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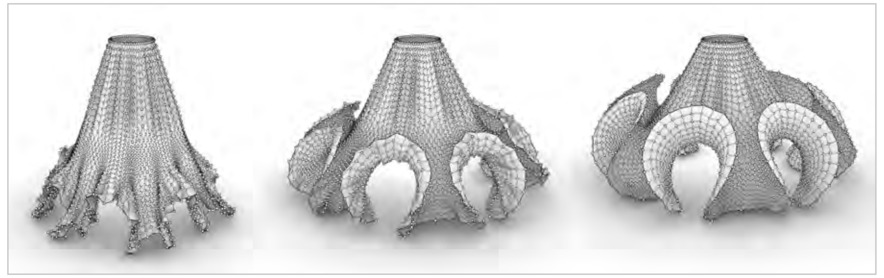

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Parametric modelling and structural analysis

The material and labour demands associated with creating a room-sized knitted form by hand made it prudent to create an accurate digital model of the desired knit geometry. An adaptive model allowed the team to envisage the overall volume spatially without having to create physical models for each iteration. Moreover, the digital formalisation allowed for the generation of the knit specification, the calculation of material quantities, and the carrying out of structural analysis.

1. *The Living Room.* A cosy, sculpted interior. © Simon Veit-Wilson.

2. Computational modelling. An idealised form was explored using a parametric model that combined an Enneper surface and a spherical dome with a central oculus. © Armand Agraviador.

3. Physical behaviour simulation. The same knit specification model as a subdivided surface with defined edge extensibility and constant directional vector force applied to act as a proxy for gravity. When anchor points are defined, the model illustrates a predicted deformation as a textile. © Armand Agraviador.

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4. Building with waste. The resource strategy was to maximise the use of waste from local industries, including Herdwick wool (4.1), sawdust from a local hardwood sawmill (4.2), and paper sludge from the papermaking industry (4.3). © Hub for Biotechnology in the Built Environment.

Through this medium, several geometric approaches were explored for relating multiple apertures to a central inhabitable volume with an oculus at its apex. After some design experimentation, a disjunctive union of a truncated hemisphere and an Enneper surface was selected for two reasons. From a visual perspective, the resulting complexity of the edges, creating apertures that narrow before intersecting the core hemisphere, produced architecturally expressive and inviting openings through which inhabitants would enter. These ‘frills’ gave a dynamic expression of movement to best showcase the two sides of the static surface – one of which would be encased in mycelium substrate, the other with exposed wool. Second, since Enneper surfaces are minimal surfaces (Weisstein, 2005), they would be consistent with the natural behaviour of a textile under tension, and they would employ an optimised use of material in terms of surface area and structural performance. The resultant saddle-like junctions have the added benefit of showcasing the double-curvature capabilities of the knitted fabric composite shell.

A one-quarter-scale maquette was knitted to test how the digitally defined surface geometry translated to a soft physical medium with a non-zero thickness. Equipped with a tactile understanding of the textile behaviour from the maquette, the digital model was adapted to reflect any desired adjustments to the relationship between the surfaces of the dome and the ‘frills’. The Kangaroo 5 plugin for Grasshopper was employed to simulate the behaviour of the mesh geometry under gravity with specified regions assumed static from tethering, as well as some extensibility factored in. By exporting the resulting geometry to Oasys GSA structural analysis software and using material properties from mechanical tests on material samples, the required depth of mycelium paste in different areas of the structure was determined to ensure that deflections and stresses were kept within acceptable limits.

Specification and control of soft knitted formwork

The dimensions for the knitted canopy were extracted from the digital model and translated into a generative knitting pattern at a rate of 19.4 wales (stitches) per metre and 26.6 courses per metre. The fabric was knitted in the round as a seamless canopy that increased across 95 courses from 60 stitches (top centre) to 802 stitches (bottom edge). Knitting was undertaken manually, without needles, using a freehand knitting process. It was essential to knit the canopy with a high stitch density and to reduce extensibility as much as possible to limit deformation of the textile formwork when 550kg of mycelium paste was applied. Control of stitch length was monitored and maintained manually as the loops were formed through a tacit knowledge of material behavior.

Resources: A local waste strategy for mycelium knit composites

Each year, the UK produces 32 million kilograms of wool, most of which is discarded as a by-product of the meat industry (Gosling and Tully, 2023). While much of this wool is unsuitable for fine yarn production, wool tops – untwisted bundles of fibres that form the interim production stage between fleece and yarn – offer an alternative large-scale material for off-machine freehand knitting. Early lab tests showed that coarse wool processed into wool tops provides an excellent interface for mycelium growth. Herdwick wool, from sheep living on the fells of the Lake District in the north of England, was selected as a local source of textile fibres for knitting the canopy that provided the formwork and interior surface of *The Living Room*.

Alongside this, analysis of industrial waste streams available in the north of England identified cellulose-rich waste produced as a by-product of the local timber and papermaking industries. Hardwood sawdust from a local sawmill and paper sludge, a by-product of papermaking, were selected as suitable for the requirements of the composite. These materials are unusual in that they have no commercial value and do not feed into other industrial processes. However, further work is required to assess the quantities of these materials that are available in line with the bulk material requirements of the construction industry.

Biofabrication: On-site preparation, assembly, and growth

Biofabrication on site was undertaken in 29 days. Prior to biofabrication, a 4x4x2m-high scaffolding frame was erected in the gallery and the knitted canopy was attached and tensioned to this frame. The mycelium was pre-grown in waste sawdust from a local sawmill for seven days to ensure rapid growth once it was applied to the canopy. Biofabrication comprised autoclaving all substrate materials over a three-day period, and then moving these sterilised materials to the gallery. Preparation and mixing of mycocrete was undertaken at the same time as plastering the knitted formwork. This was completed in-situ in three days. Altogether, 550kg of mycocrete paste was applied to the 90kg wool canopy formwork. The canopy was re-tensioned regularly during application of the mycocrete paste to maintain the form as the weight of the paste caused the knitted canopy to stretch. Mycelium growth was monitored for 16 days prior to 10 days of drying. After drying, the weight of mycocrete was estimated at 150kg. At this point, all structural supports were removed to reveal a free-standing structure, which was ready for public exhibition.

Analysis and evaluation

The research demonstrates how mycelium can be grown on a large-scale knitted formwork to achieve a multifunctional composite using waste materials. The results show that a 90kg knitted wool canopy can be supported by an average 3cm-thick layer of mycelium paste to achieve a self-supporting thin shell-like structure. The experience of inhabiting *The Living Room* is in stark contrast to the gallery in which it is located. The interior is defined by soft knitted wool. The exterior is formed from mycocrete, which is predominantly characterised by a white mycelial skin, but the surface is also coloured by the varying batches of waste paper sludge and by water applied during growth. The thermally insulating properties of the wool/mycelium composite produce a warm, tactile environment. The soft, curvaceous interior contrasts with the hard, white rectilinear gallery space. The wool absorbs sound, transforming the acoustics of the space inside *The Living Room* to generate a noticeably different experience to the gallery outside.

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5. Mycelium + knit. Close-up of mycelium paste grown on a knitted fabric, showing the integration of the mycelium into the wool to create a robust composite material. © Ben Bridgens.

6. Freehand knitting. 90kg of Herdwick wool tops were knitted by hand to create a seamless, single-piece knitted canopy. © Jane Scott.

7. Knitted canopy installation 1. The central oculus was supported by a temporary steel ring and was lifted into position using ratchet straps supported by a temporary reusable scaffold frame. © Ben Bridgens.

8. Knitted canopy installation 2. The final form of the canopy was determined on site by tensioning the perimeter. A temporary, reusable hosepipe was installed around the perimeter to ensure smooth curvature and to distribute load from the tensioning straps to the knitted fabric. © Ben Bridgens.

While the research outcome is materialised in *The Living Room*, the findings reflect on the results of technical experimentation tested at an architectural scale over a six-month period. Evaluation focuses on the impact of scale and waste materials on the biofabrication of biohybrid textile architecture composed of wool and mycelium.

Waste as a resource for biofabrication

In general, waste materials are not uniform in their composition. In the waste sourced for this project, the colour of paper sludge, and the fineness and mix of wood species of sawdust, varied between batches. Nevertheless, to achieve good mechanical properties, consistent growth is required. Non-standard materials required further processing, pre-sorting, and blending to ensure consistency for the paste. This work was approached with a craftsperson-like mentality, using tacit knowledge to carefully assess the consistency of the paste and maintain a suitable viscosity for plastering and subsequent growth. Findings from this research suggest that, as the use of non-standard materials for biofabrication increases, adaptive processes need to be developed that can flexibly adjust to a variety of inputs.

By taking the knitting process away from industrial knitting technology, the freedom to work with unconventional materials at a large scale was achieved. In addition to the potential to use non-standard waste materials, our research identified that the use of loosely organised fibres within wool tops – rather than tightly twisted yarns – enabled excellent mycelium growth through the textile, leading to enhanced integration of the biohybrid composite.

The application of mycocrete render was undertaken by hand over a three-day period. During this time the application was monitored to test the depth of mycelium render on the knitted formwork. It was essential to achieve the depth of paste determined by structural modelling to ensure structural stability, and so manual assessment was required throughout to check the depth of paste on the complex curved surface.

Biofabrication for the scale of the built environment

Biofabrication with living materials such as mycelium at a large scale is challenging prevailing processes and requires rethinking of known design practices. For consistent growth to occur, light, temperature, and moisture must be regulated. In the research, this was achieved by building a 4x4x2m-high scaffolding frame on site, and by covering it with reusable tarpaulins to create a dark, warm, moist growth chamber. The advantage of this approach was that the scaffolding, which is widely available and reusable, also provided a framework on which to hang and tension the knitted canopy formwork. During growth, humidity was maintained by spraying the enclosure regularly with water, and optimal growth temperature was achieved using the gallery's existing efficient air-source heat pump heating system.

Contamination with other microorganisms can be a significant challenge for the biofabrication of mycelium composites. Contamination leads to poor growth, discoloration, and poor mechanical properties. Therefore, environmental controls and clean working conditions during preparation and growing are critical. Early experimentation on adapting the mycocrete recipe for

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waste materials highlighted additional challenges of contamination within the sawdust and paper sludge. Autoclaving all materials at 120°C for a minimum of 30 minutes was necessary to prevent contamination during the growing period. However, because of its size, it was not possible to autoclave the wool canopy. Instead, the canopy was cleaned using 70% ethanol spray prior to application of the mycocrete paste. Despite this, some contamination did occur in particular areas of the surface where water was able to accumulate. A protocol to monitor and remove contamination was developed over the course of the growing and drying stages. Daily checks were undertaken, and contamination was removed by gently wiping with dilute ethanol or soapy water.

Shrinkage of the mycocrete render had been anticipated. While shrinkage of a simple mycelium block is easy to predict, both the scale and shape of *The Living Room* made it difficult to model how shrinkage would impact the overall form. When applied to the structure, mycocrete contains 75% water, and to stop mycelium growth the structure is air-dried in typical room conditions. This led to a loss of 20cm (equal to 10%) in height at the middle point of the structure after three months. Controlling shrinkage remains a challenge, especially when working with textile formwork that also displays dynamic moisture-regain properties. In addition, drying and shrinkage caused some small cracks to appear in the bottom part of the frills. More research and data are needed to be able to calculate the impact of shrinkage on the overall design and performance at scale and over extended time periods.

9. Plastering. The mycelium paste was applied by hand to thicknesses determined by structural analysis. © Ben Bridgens.

10. Scaffold removal. © Ben Bridgens.

11. *The Living Room.* A freestanding, 4m-diameter knit and mycelium composite structure made from local waste materials. © Ben Bridgens.

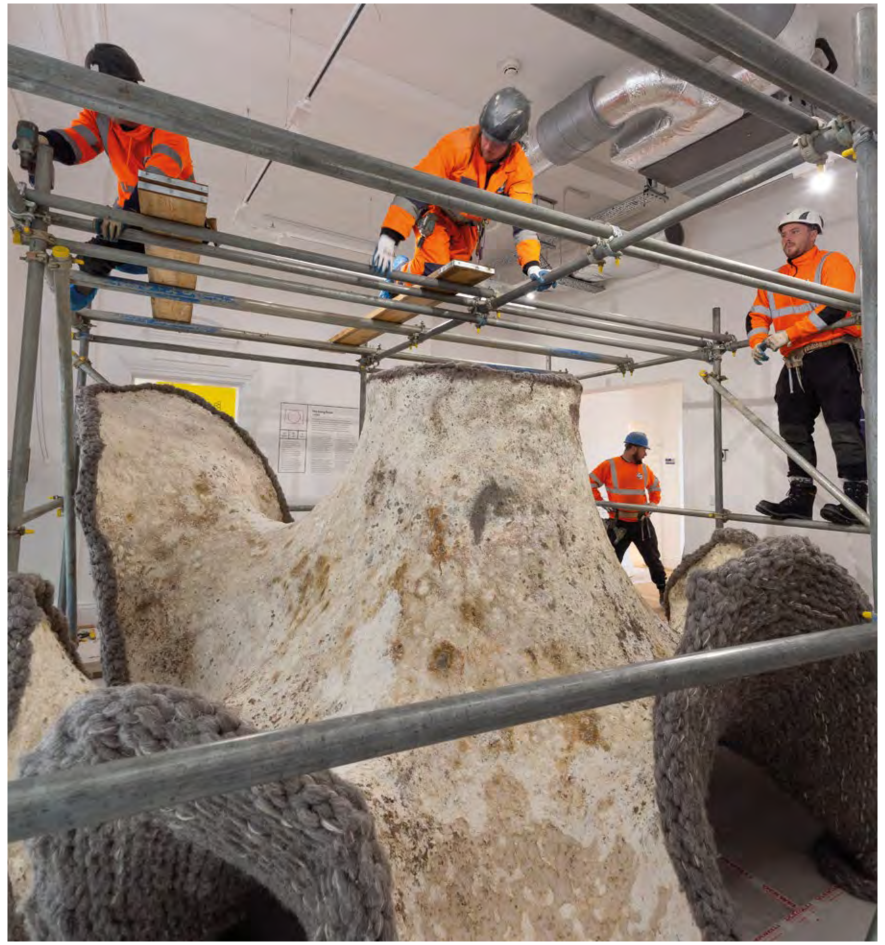
The results of this research show that the growth chamber design is critical to success. It is vital to achieve optimal growth conditions – in terms of darkness, temperature, and moisture level – throughout the structure for the duration of the growth period to ensure rapid, consistent growth and to avoid unwanted growth of other microorganisms. Sterile growth chambers within small-scale lab environments are well understood, with sophisticated controllable systems available. The creation of large-scale bespoke growth spaces is challenging, particularly when it relies on having a secondary, accessible clean environment within a building or on site.

Conclusion

The Living Room demonstrates how textiles and biotechnology can enable circular processes for the built environment, where industrial by-products and waste from one industry can be appropriated as resource for another sector. Biohybrid textile architecture addresses critical questions focused on the transformation of established industrial practice to develop digitally enabled, regenerative biofabrication technologies, which are required to design and make architecture in a resource-challenged world.

The research undertaken for *The Living Room* required a workflow that integrated computation with craft sensibilities. While parametric modelling and structural engineering software determined the design parameters, large-scale biofabrication relied on a tacit knowledge of mycelium composite paste, knitting methods, and microbial/textile interactions. Iterative prototyping has been essential to understand the influence of each parameter and build knowledge throughout the design and biofabrication processes.

The research provides an opportunity to create new architectural expressions that emerge when a structure is grown rather than built. The significance of *The Living Room* is manifest not only in the technical challenge of growing a composite from textiles and mycelium, but more importantly in the way that the process of growing a composite using soft, tactile textiles can generate a new spatial experience. *The Living Room* transforms the interior environment thermally, acoustically, and texturally, presenting a vision for responsive bioarchitecture that anticipates new ways to inhabit the built environment.



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Acknowledgements

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FROM WALLS TO ROOFS
FORMWORK-FREE ROBOTIC EARTHEN VAULT CONSTRUCTION

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Introduction

The dwindling availability of construction material resources poses a significant challenge that calls for innovative solutions to address material scarcity and waste. In response to this challenge, this research paper sets out to leverage the potential of computational design and robotic additive manufacturing to explore avenues for sustainable construction practices.

At the intersection of ancient principles for Nubian vault brick construction and contemporary methods of additive manufacturing, this paper introduces a large-scale architectural experiment to reimagine the additive construction process by harnessing the untapped potential of non-planar 3D printing. This research explores the feasibility of constructing an architecture-scale Nubian vault using 3D-printed adobe. The objective is to bridge the gap between traditional building techniques and robotic manufacturing processes, demonstrating the adaptability and sustainability of ancient architectural principles on the material and structural levels, in the context of contemporary construction practices.

The experiment focuses on replicating the distinctive structural qualities of the ancient Nubian vault, explicitly its self-supporting arches, into non-planar large-scale 3D printing, shedding light on some of the challenges associated with toolpath design, material mixtures, and drying times.

The paper highlights an iterative research process, where various geometric configurations are first tested on a smaller scale before progressing to the construction of an architecture-scale prototype. The small-scale experiments, made of 3D-printed clay, allowed for the exploration of different vault and dome geometries and parameter optimisation to ensure structural stability. The insight gained from the preliminary experiments informed the successful realisation of a full-scale Nubian vault utilising locally sourced adobe as a viable alternative to 3D-printed clay, creating a sustainable and culturally significant large-scale prototype.

Moreover, the experiment demonstrates the utilisation of self-sufficient, mobile industrial robotic 3D printing and pumping platforms, enabling a sustainable workflow that encompasses the gathering of locally sourced materials. By leveraging this integrated approach, the research

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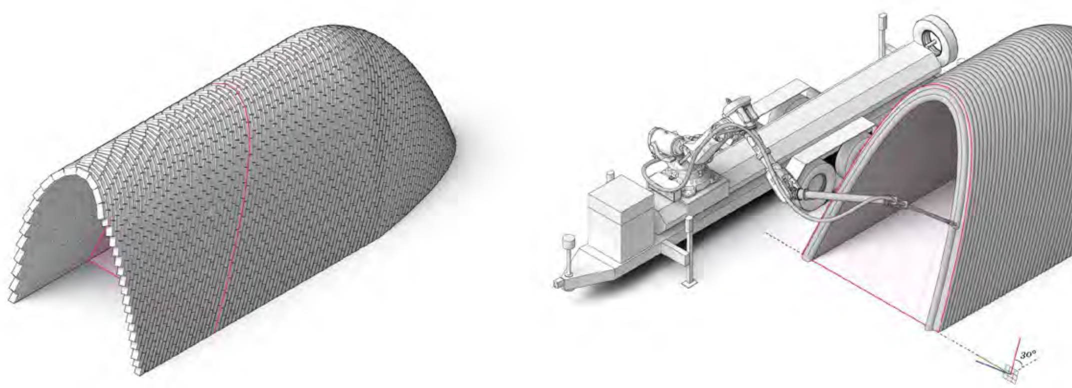

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emphasises the importance of resource efficiency and fabrication sustainability. This workflow points towards a future where the scarcity and obstacles associated with traditional resources can potentially be mitigated through innovative and environmentally conscious construction practices.

Printing the roof

Construction 3D-printing projects are predominantly recognised for the production of vertical walls composed of planar 3D-printed layers. In this process, concrete or other paste materials are pumped and robotically deposited in layers following a programmed toolpath. Given that the deposited material does not reach a fully hardened state and that every printed layer relies on the structural support of the preceding layer for stability, it is challenging to print steep overhangs or horizontal surfaces. These problems make roof construction using additive manufacturing difficult.

In the field of 3D-printing architecture, the roof has long been a largely unexplored endeavour. Perhaps the first 3D-printed roof was fabricated by the Italian company D-Shape in 2010 for the Milan Triennial (D-Shape, 2010). The fabrication of this roof was achieved using large-scale binder deposition with magnesium oxide. Implementation of such a process creates a support structure using the material that is unsolidified in order to reinforce the gable roof during the printing. AICT, a 3D-printing construction company based in California, fabricated a series of barrel-vaulted roofs by printing semicircular extrusions as concrete prefabricated elements that could then be lifted and rotated to create an enclosure (AICT, 2022). Another example of overhead structures, a ceiling in this case, was fabricated by the Block Research Group at ETH. In this example, a 3D-printed formwork whose geometry had been structurally optimised was used to create prefabricated concrete floor tiles (and subsequently a patterned ceiling) in which thin vaults were stiffened by diaphragms to create a structurally optimised horizontal overhead surface (Block *et al.*, 2017; Rippmann *et al.*, 2018). In each case, the construction of the roof using additive manufacturing is accomplished through the use of formwork and prefabricated elements that are moved into place, rather than printing the roof structure in-situ.

Supporting structures

The quest to construct long-spanning roofs can be traced back to ancient Egypt. Adobe barrel-vaulted structures were constructed using a variety of masonry techniques to achieve vaulted storerooms within adobe temples (El-Derby and Elyamani, 2016). Ancient Roman architecture continued to advance techniques for large-span structures using concrete masonry, with the Pantheon being perhaps one of the most notable examples (Cowan, 1977). Analysing vernacular architecture as a historical precedent unveils the diverse materials, structural configurations, and construction methods that distinguish different regions of the world. In the context of roof construction, vernacular dwellings historically utilised materials such as timber, turf, stone, and adobe. Regions lacking abundant timber resources took advantage of creative methods to construct structures that harnessed compression, such as vaulted roofs, arches, and domes. In most cases, the construction of these roof structures required the use of timber as a structural formwork material, or soil, which could be removed after the structure was completed.

Corbelling is a method of vault construction used by many civilisations that had not yet developed curving arches and is a method that involves the successive placement of masonry elements in layered cantilevered arrangements to form spans. This can be seen in Mayan temples or in the Cardenha buildings in Vale de Poldros, Portugal, where drystone masonry is used in the construction of the roof (Martynenko, 2017). Mediterranean tile vaulting is another notable method that gained prominence in medieval Spain and was introduced to the US by Guastavino (Ochsendorf and Freeman, 2010). This method makes use of thin ceramic tiles in structural vaulting in which minimal formwork (centring) is required during construction. Regions constrained by timber scarcity, such as the Saharan desert, explored alternative methods to roof construction that did not require any use of formwork. The ancient Nubian technique entailed inclining layers of brick in the shape of a parabola towards a rear wall, referred to as the 'espar', to efficiently transfer forces from the temporary structure with minimal tension and bending (Dahmen and Ochsendorf, 2012).

1. In-progress 3D-printed vault during construction. © Barrak Darweesh, Ronald Rael, University of California, Berkeley.

2. Illustration of masonry construction patterns translated to 3D-printing toolpath logic depicting the vault's slicing angle and nozzle orientation. © Barrak Darweesh, Ronald Rael, University of California, Berkeley.

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3. Merging Nubian vaults 3D-printed in clay. © Barrak Darweesh, Ronald Rael, University of California, Berkeley.

4. 3D-printed apse using non-planar material deposition. © Barrak Darweesh, Ronald Rael, University of California, Berkeley.

5. Multi-axis extrusion and nozzle orientation. © Barrak Darweesh, Ronald Rael, University of California, Berkeley.

Building on tradition

Bridging the past and the present, ancient masonry construction shares intriguing similarities with the more recent large-scale 3D-printing process, particularly in aspects such as material behaviour, repetitive layering, and the instability of the discrete unit. Masonry structures are built from brick units, which are connected sequentially using mud or mortar, taking their final stable form when the material dries or sets. Similarly, the structural integrity of 3D-printed layers of extruded material is dependent on layer adherence and the drying of the material throughout the construction process. Both masonry work and large-scale 3D printing rely fundamentally on stacking layers of identical components in a repetitive manner. Every layer in both processes is intrinsically dependent on the previous layer to ensure structural stability. This similarity also implies a shared vulnerability in which inconsistency and misalignments can propagate throughout the structure, causing global failures.

Drawing a parallel with traditional masonry construction techniques, most approaches to construction 3D printing use planar layers. When constructing curved forms, this approach can be compared with corbelled masonry, where the geometric contouring of arched shapes like vaults and domes leads to a distinct stair-stepping appearance, resulting in non-uniform layer displacements. On the

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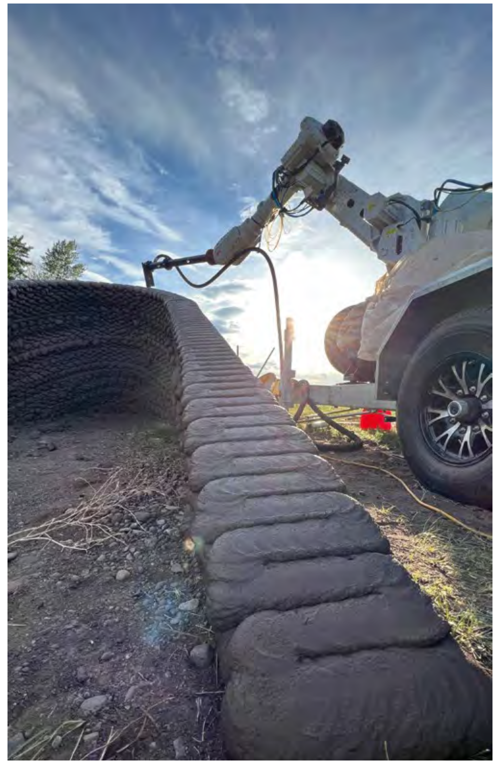

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contrary, the experiments discussed in this study take advantage of non-planar 3D printing, ensuring that the printed layers correspond with the line of thrust, culminating in structures that are entirely in compression. This approach is comparable to domes or arches that are constructed using brick joints, which are aligned at right angles to the line of thrust, often referred to as 'true' domes.

Early experiments

To better understand the viability of 3D printing unsupported forms using a viscous, structured fluid, it was essential to first gain insight through small-scale prototypes by testing various aspects of the design and fabrication process. In these preliminary experiments, clay served as the primary 3D-printed material. The plastic tubes are filled with clay and mounted on an end-effector of a robotic arm, where a motorised piston within the tube facilitates the clay extrusion through a nozzle during the printing process.

Drawing inspiration from traditional brick construction, the geometric forms printed during these tests are not sliced into planar layers. Instead, non-planar toolpaths are utilised, operating in multiple axes and nozzle orientations simultaneously. The prototypes were used to examine various geometric forms such as vaulted structures, arches, apses, squinch domes, and merging vaults. The objective was to understand how these forms can be realised through strategic toolpath planning, without the requirement of a supporting auxiliary structure. Concurrently, some tests explored surface texturing and local toolpath strategies, aiming to gain an understanding of how the weight of the extruded material affects the unsupported geometry, especially when scaled up to a larger prototype.

At the platform level, the experiments demonstrated the capabilities of both 3-axis and 6-axis robotic configurations, highlighting the benefits associated with multi-axis extrusion, such as even material deposition, made possible by conforming to the curvature of the printed geometry. Additionally, testing various platforms allowed for a better understanding of the forms that are achievable even when utilising some of today's commonly used 3-axis gantry-style robotic platforms.

The series of experiments conducted provided valuable insights into the material behaviour, potential geometric configurations, and viability of 3D-printing long-spanning unsupported structures. The knowledge gained laid the foundation for the subsequent large-scale prototype.

6. 3D-printed adobe following a square-wave toolpath pattern. © Barrak Darweesh, Ronald Rael, University of California, Berkeley.

7. In-progress 3D-printed vault during construction. © Barrak Darweesh, Ronald Rael, University of California, Berkeley.

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8. Aerial view of the 3D-printed vault during construction. © Barrak Darweesh, Ronald Rael, University of California, Berkeley.

9. Front view of the 3D-printed Nubian vault after mud-plastering the outer surface. © Barrak Darweesh, Ronald Rael, University of California, Berkeley.

10. Rear view of the 3D-printed Nubian vault after mud-plastering the outer surface. © Barrak Darweesh, Ronald Rael, University of California, Berkeley.

11. Wall texture detail of the 3D-printed adobe surface. © Barrak Darweesh, Ronald Rael, University of California, Berkeley.

In-situ 3D-printed Nubian vault

The full-scale experiment took place in La Florida, Colorado, a location that has a rich tradition of using adobe in construction as a consequence of its natural abundance of alluvial soils possessing the ideal ratio of sand, clay, and silt for the production of earthen buildings. The readily available soil is excavated and mixed with water and straw, which is used as a binding agent, to create an adobe mixture to serve as the 3D-printing material throughout the experiment. The adobe mixture is characterised by its ease of tunability through adjusting the dirt to water ratio. Printing tests revealed a direct correlation between the material's workability and structural integrity during the printing process. Mixtures with higher amounts of water have proven to flow easier through the pumping system, while lower water content resulted in a more structurally stable mixture, preferable for proper layer adhesion. Given these observations, an optimised mixing ratio was paramount to facilitate a smooth printing process that ensures the stability of the printing object without clogging and interrupting the pumping system.

Geometry

The Nubian vault designed for this experiment measures 5m in length, 2.5m wide, and 3m in height. The geometry consists of an apse and a vault, both made of a series of translated catenary arches. These arches originate from the ground level, and lean at a 30º angle, to first make an apse followed by an extruded Nubian vault. The toolpath takes the form of a square wave varying in amplitude in different regions of the toolpath. At the base, the square wave amplitude measures approximately 30cm, making a stable base. Towards the upper profile of the vault, the amplitude is reduced to approximately 20cm. This intentional reduction in the toolpath amplitude first aims to reduce the weight of the upper, unsupported regions of the vault, and to optimise stability while minimising material usage.

Equipment configuration

The configuration for printing the vault consisted of a mobile, 7-axis industrial robotic arm mounted to a rail built upon a 6m-long flatbed trailer. The robotic arm has a total reach of 3.2m and is placed on a 5m linear track covering the entire span of the printed Nubian vault dimensions. The entire configuration is designed with a wheeled, towable base allowing it to be transported to the construction site for in-situ printing. The additional degrees of freedom of the industrial robotic arm offer

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precision in material deposition when printing non-planar layers. By allowing the nozzle to orient in a perpendicular direction to the printed toolpath, the platform guarantees consistent layer deposition and uniform extrusion throughout the printing process. The setup includes an integrated gas-powered pump, designed to channel the adobe mixture to the robot's end-effector.

The process of preparing the adobe mixture consists of excavating soil near the printing site, which is then sifted to eliminate any aggregate sizes not able to be pumped by the printer. The sifted soil is then mixed with water and straw before being transferred to the hopper of the extrusion pump.

Material

Most recent construction 3D-printing projects primarily use concrete as the extruded material. This preference stems from the well-understood properties offered by concrete and its widespread use in traditional construction. However, this study aims not only to demonstrate the use of a material with a lower environmental impact, but also to highlight the advantages associated with using adobe as a 3D-printing material. It is important to note the challenges when using 3D printing concrete to highlight some of its constraints when compared with 3D printing adobe. In a precise instance, one of the critical factors when using 3D-printed concrete is the limited time window during which the material remains workable after being mixed. The implications of such time constraints translate to the inability to accommodate any delays in extruding the mixed concrete, or to tolerate disruption to the 3D-printing process, as such disturbances can jeopardise some of the components in the pumping system, such as the hose or the extrusion pump, as the material begins to set. The 3D-printed vault demonstrated in this study is constructed entirely using natural, locally sourced mud. The absence of a chemical reaction to induce hardening in the extruded material simplifies considerations related to material workability durations or curing periods. Unlike concrete, adobe solidifies gradually by drying, rather than through chemical reactions, employing only wind and solar exposure, which offers a desirably forgiving printing process.

In the execution of this experiment, the vaulted structure was segmented into multiple toolpath sections, allowing every section to adequately dry before the continuation of the printing process. One of the key elements influencing the durations between the printed sections is the prevailing weather: sunny and breezy conditions expedite the drying process. To ensure controlled drying and stability, wood shoring was occasionally used during the construction. However, this was not needed to support the apex of the roof, but rather the leaning walls that extended at the base of the structure. A notable challenge in assessing when to safely add more printed layers is that, while the external surface of the 3D-printed adobe may appear to be perfectly dry, its interior core can remain damp. Thus, proper drying is entirely contingent upon weather conditions, although in the experiment a large fan was used to assist in the drying of the structure. Because drying does not occur quickly inside the hose after printing has completed for the day, the pump and hose can be left overnight without needing to be emptied and cleaned. A simple measure, such as covering the pump to shield it from sunlight and wind, is sufficient to prevent the material from drying. Thus, a seamless continuation of printing can resume immediately, as there is no need for equipment cleaning or platform recalibration between the printed sections.

To ensure the preservation of the 3D-printed adobe structure and prevent the accumulation of water in the cavities formed by the printed texture, the vault was coated with two layers of mud plaster composed of the same admixture as the adobe. This coating yielded a smooth exterior finish, primarily purposed for preservation, while the interior of the vault kept its original surface texture, showcasing the visible 3D-printed layers.

Towards self-sufficiency

The study aims to present a forward-thinking approach to the challenge of material scarcity in construction. Despite significant advancements in construction technology, the industry relies predominantly on concrete, a material with a harmful environmental footprint. The experiment presented here takes advantage of a material that has proven over millennia to be a dependable construction medium, in addition to the various highlighted benefits associated with using it in construction 3D printing, such as its abundance, smooth printability, and environmentally benign footprint. As previously noted, the robotic infrastructure utilised in this research emphasises mobility and self-sufficiency, aiming to harness materials that are both abundant and indigenous to the construction site where the platform is deployed. The study proposes a framework that affirms the significance of drawing insight from traditional and ancient construction crafts. By combining traditional, time-honoured techniques with contemporary construction technology, this project aims to arrive at new possibilities that redefine the boundaries of large-scale 3D printing.

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12. Interior view of the 3D-printed vault. © Barrak Darweesh, Ronald Rael, University of California, Berkeley.

13. Rear view of the completed formwork-free, 3D-printed adobe Nubian vault. © Barrak Darweesh, Ronald Rael, University of California, Berkeley.

14. Front view of the completed formwork-free, 3D-printed adobe Nubian vault. © Barrak Darweesh, Ronald Rael, University of California, Berkeley.

15. The completed formwork-free, 3D-printed adobe Nubian vault. © Barrak Darweesh, Ronald Rael, University of California, Berkeley.

FARMING SECURE WATER
RESITUATING THE WATER–ENERGY–FOOD NEXUS WITHIN RECOMBINANT BUILDING ENVELOPES

MANDI PRETORIUS / ANNA DYSON
YALE CENTER FOR ECOSYSTEMS + ARCHITECTURE

Out of necessity, informal settlements across the globe will lead the way towards novel circular, renewable resource economies. Within this context, distributed household water collection and management could support how households facilitate water governance through the shaping of on-site water resource access that intersects with energy and food security. Here, a strategy for on-site plant-based water purification is presented as a multivalent mediation of resources for household water safety, one that eco-systemically intersects with the management of thermal gradients and daylighting. Through an open-architecture framework titled Solar Enclosure for Water Reuse (SEWR), we resituate the water–energy–food nexus by shifting the site of resource control and management from brittle, centrally controlled, industrial-scale infrastructures, to hyper-localised building interfaces that tightly couple the concentration of bioclimatic flows with the collection and purification of energy and water through distributed building envelopes. Within informal, semi-formal, and even formal building fabrication typologies, SEWR provides a parametric framework to match available bioclimatic resources to context-appropriate optical and biochemical fabrication technologies that collect, purify, and store water and energy. In the context of both informal settlements and food deserts within developed regions, SEWR aligns with burgeoning urban farming movements. Through harvesting sunlight and edible plant-based dyes that can be grown on site, regenerative building systems simultaneously address occupancy needs for high-quality food, thermal comfort, daylight, and clean water.

The SEWR framework is a recombinant ecosystemic framework that incorporates biological and climatic flows into building envelopes, with the guiding ecosystemic design criteria of addressing human health and wellbeing through the modulation of light, thermal gradient, and water (Fig. 2) (Dyson *et al.*, 2015; Novelli *et al.*, 2021). Each embodiment of the SEWR research framework shapes incident solar energy for multivalent needs. Focusing on the household, in which daily water, energy, and food requirements interdependently define household security, the proposed embodiment investigates the circular availability of renewable energy and bio-based materials, and their impact on the building-scale systemic approach to safely treating water year-round. Further, the system adapts towards qualitative considerations of hyper-local sites, in terms of *how much of what kind* of ambient resource is available to meet fluctuating needs, and how that should inform the

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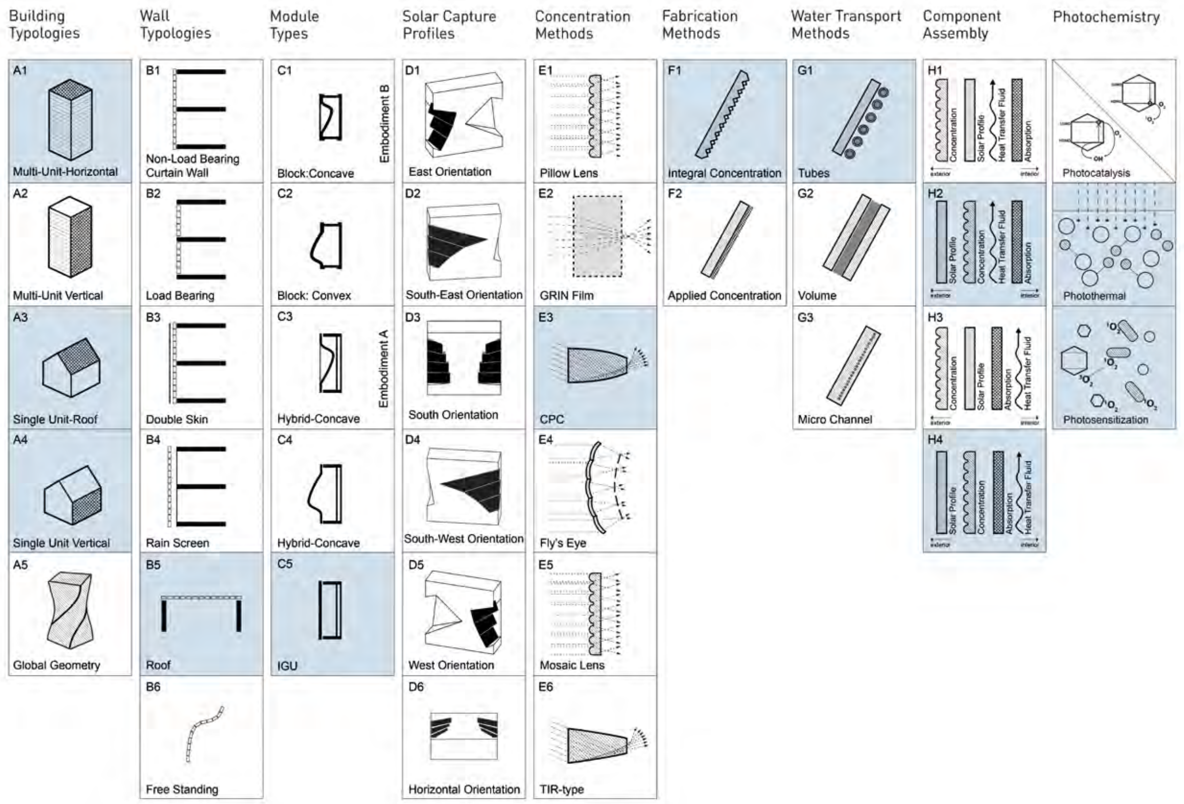

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technical and fabrication strategy, quantitatively, in terms of facilitating rapid solar purification within tight periods of solar access, for building sites and climates that may not have adequate surface area or extended sunny periods. The proposed system (Fig. 6) aims to fundamentally challenge assumptions concerning the performance of advanced materials with applications in 'non-expert' environments. In particular, we test the viability of applying low-cost optical methods that require tight tolerance thresholds in manufacture and assembly, with the incorporation of home-grown biological extracts into a material assembly that could, for the first time, support daily means of safely accessing water that is purified from viruses and pathogens, in a low-cost, non-toxic, and democratic model.

Recombinant assemblies: Decentralising resource access by bridging material flows across informal settlements

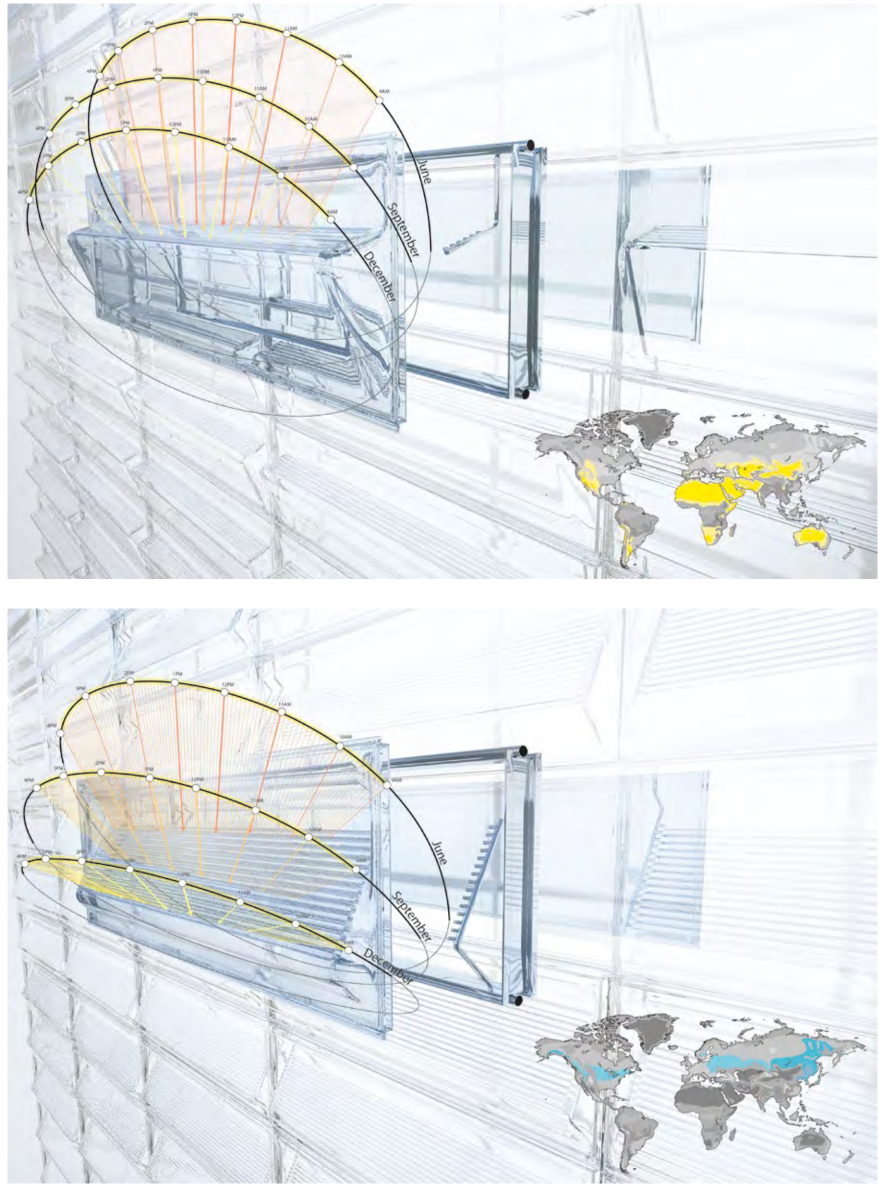
Resource insecurity with climate-associated migration and urbanisation is set to intensify, as up to a third of the Earth's projected 9.7 billion population will live in informal settlements or housing without on-site access to basic services by 2050 (UN-Habitat, 2022). The hybrid decentralisation of resource management is a viable alternative to the steep economic and environmental costs of resolving access with centralised systems (Hutton and Varughese, 2016; IFPRI and Veolia, 2015; Teodoro and Saywitz, 2020; Wutich *et al.*, 2023). Extending access to on-site water management could decouple households from rising consumer water prices linked to the failure of centralised infrastructures, directly benefiting community-level resource security and reducing the economic marginalisation of increasingly commodified access to centralised utility services if viable and sustainable point-of-source solutions are developed (Pretorius, 2023).

The future of circular economies is inexorably linked to the material flows of informal urban settlements, which, despite eluding official databases, move extensive matter flows and are, out of necessity, models of circularity (Marino and Pariso, 2022). Of the many trajectories in shifting to a sustainable built environment at both policy and technology levels (decarbonisation, on-site renewable energy, water generation, circular material economies) (UNEP and Yale CEA, 2023), few of these materials and technologies can be accessed by informal or low-income households who struggle every day with basic access to water and energy. Low-cost systems for indigent households must, as will all advanced building systems in the future, take account of circular economies.

Approaching the built environment as an open-architecture framework (Dyson, 2002) within which multiple emerging techniques and interests could be programmed, we develop several critical resources into an approach to building using adaptable, low-cost, deployable fabrication techniques for disparate contexts.

1. SEWR Embodiment: Façade-integrated ambient water capture of airborne humidity through bio-based hydrogels and solar water purification through optical modules, 2018. © Yale Center for Ecosystems + Architecture.

2. The Solar Enclosure for Water Reuse (SEWR): An open-architecture framework for managing on-site solar water purification alongside daylighting, thermal and energy management. Adapted from US Patent No. 9,090,486. © Dyson *et al.*, 2015.



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3. SEWR Embodiment: Solar geometries adapted to bioclimatic regions deployed as optical glass bricks, 2011. © Yale Center for Ecosystems + Architecture.

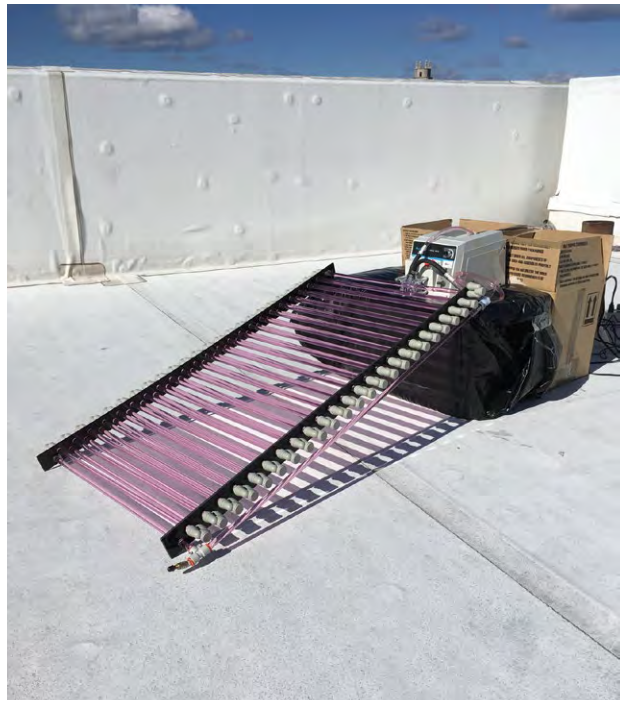
Elements of the water–energy–food nexus are used to directly inform a prototyping approach that seeks to use renewable and cyclical means of achieving each need through fundamental physical principles: water, light, heat, energy, and power. Instead of a product-solution approach limited to a single function, incorporating water management into building envelopes leverages the extensive multi-functionality already accommodated in building systems and engineered materials. Demonstrating how building systems could produce significant resource-shaping within both individual households and cumulatively in the built environment, augmenting multi-functional water treatment into existing building requirements such as roof and glazing enclosures also ensures that informal and self-built structures can add on-site water treatment capacity using available materials as minimally and effectively as homeowners can afford.

Distributing water systems by embedding multi-functionality into mass-manufactured building materials

The proposed building assembly embeds novel design criteria for distributed water treatment into manufacturing processes, which factor scalable means of ensuring decentralised access by all kinds of building actors, from informal homebuilders to housing authorities. Although the SEWR framework can take on many embodiments, the featured instance of the approach here demonstrates a low-cost approach to strategically integrating SEWR within informal housing settlements with the plastic roof-sheeting assembly type (Fig. 6). As both the modular system unit and a widely accepted form of building enclosure that has been adopted in various climates with local structural, environmental, and vernacular criteria, common corrugated plastic sheeting is deployed provisionally to house processes for the collection, purification, and storage of ambient water. Solar-concentrating optical principles are incorporated into an insulated glazing assembly for roofing: the optimised optical profile based on curvature relative to a focal point in two dimensions is scaled and extrapolated into an extruded geometry akin to corrugated sheeting, to give additional value and functionality to the corrugations or ribbings of a roof sheet geometry to produce interlocking, lapping, and spanning functions. The approach uses the scalable, ergonomic logic of standardised roof sheeting and inexpensive glazing treatments for manufacture, distribution, and construction that could competitively incorporate extrusion, thermoforming, or modular injection moulding into a localised production model. The adapted optical geometry emulates a sufficient ribbing profile for structured roof sheets. Logistically, the collector assembly harnesses modularity with flat-pack and stackable attributes scaled for handling by one or two people and easy transport to a site with a domestic vehicle. Once installed, the glazed roofing system produces a form that shapes light and converts solar energy for water treatment, heating, and power while shielding components and enclosing the building interior using a lightweight assembly with selectively programmed surface and material behaviours. Most occupant-built informal to formal housing uses low-cost sheeting as roof enclosure materials that are reused or readily traded within circular economies of informal settlement networks (Celentano and Habert, 2021). Therefore, in addition to the simple structural uses of mass-manufactured building materials, further embedding functional capacity for on-site water treatment into readily available, standardised building components could allow individual households access to renewable water treatment techniques at minimal additional cost, provided they are coupled with the elevation and extraction of the plant-based dyes.

Socio-ecological security

Several synergistic disinfection treatments that harness qualitatively different conditions are incorporated: solar pasteurisation (SOPAS), UV, and visible-spectrum photosensitiser-enhanced solar water disinfection (SODIS). With the latter, photochemical processes driven by photons or photovoltaic energy could shift how we consider resource pathways towards scaling systems to better associate with the needs and resources of the context. With these prototypes, we investigated photosensitising materials that could be harvested and cultivated from food-growing plants and added as an edible solution that enhances solar disinfection by broadening the spectral range to include visible light, in addition to ultraviolet energy (Figs. 4, 5), such that water safety can be visually verified, since the colour indicates the presence of pathogens. The photosensitiser can be sourced from a combination of common plants, such as chlorophyll-rich alfalfa or curcumin compounds in turmeric in conjunction with quinoa and soybean extracts as natural dispersants (Ryberg *et al.*, 2020). This is an effective technique to control waterborne viruses, which widely available filtration devices, such as ceramic filters, do not remove. Most importantly for a solar-driven system, the incorporation of concentration optics with plant-based photosensitisers reduces water treatment time to ~20 minutes from a process that would otherwise take hours to inactivate pathogens with sunlight alone (Ryberg *et al.*, 2018). This renders the system viable across the alternating rainy and dry seasons that are typical throughout equatorial regions.



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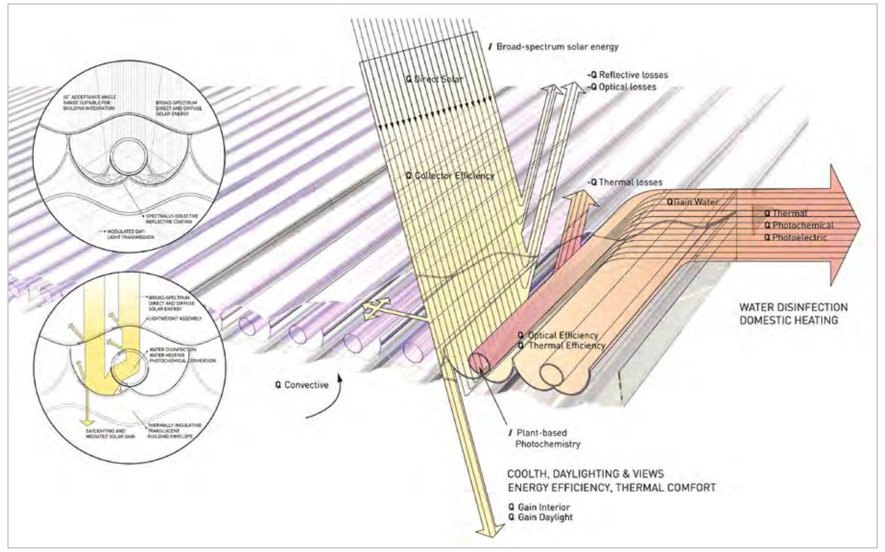
4 & 5. SEWR Embodiment: Incorporating plant-based edible photosensitisers into household water treatment practices that provide a visual indication of safe drinking water when the fluid runs pink to clear. Demonstration at UNEP Headquarters, Nairobi, Kenya, 2019. © Yale Center for Ecosystems + Architecture.



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6. SEWR Embodiment: Incorporating plant-based water disinfection into low-cost multifunctional building envelopes that remediate solar heat gain while offering cool diffuse daylighting to the interior spaces, 2022-2023. © Yale Center for Ecosystems + Architecture.

There are many barriers to household water treatment arising from the conditioned bias towards centralised 'formal' systems, climate dependence on renewable energy, and the 'low-tech' connotations of biomaterials. The proposed incorporation of photosensitiser-enhanced SODIS shifts this perspective by introducing scalable testbed conditions with linear attributes that suit the needs of researchers while limiting complexity to ensure maximum water safety and harnessing water's plural properties – optical, thermal, consumable, harvestable – as assets in the system design. Simple and effective means of indicating water safety are essential in decentralised water management. In addition to microbial inactivation, the plant-based dye provides a visual indication of the water treatment process, as the visible colour's photodegradation to clear correlates with the treatment time and indicates when the water is safe to drink. The visual indication of water safety plays a significant role in the perception of water security and potability, not to mention how the aesthetic properties of taste, smell, and colour inform a household's trust and adoption of a particular technique. The system combines the visual qualities of a dye-enhanced solar water treatment process with the transparent daylighting criteria of a roof lighting system that benefits from the aesthetic colour rendering of transmitted light, and a visible measure of water safety relative to view-finding through the window aperture. Simplified as a flow-through system running the spanning length of a roof sheet, building occupants look up and through an aperture to view the sky with visual glare. Light entering the building provides sufficient view, cool daylighting, and recognisable water safety to household occupants, without the perception of complexity.

Simulation of optical and photochemical enhancement of water

The optical design incorporated methods in geometrical optics (Winston *et al.*, 2005), and commensurate procedures in building-integrated optics and solar-concentrating energy systems. The proposed system (Fig. 6) could assimilate with common housing typologies in self-built structures and informal housing; the two-dimensional CPC profile is extruded for incorporation into a roof sheet and inclined along the roof-sheet length to the optimal tilt angle (OPTA) to ensure that sunlight falls onto the collector closer to the direct normal angle for most of the year to reduce surface cosine and reflectance losses. Initial raytracing focused on validating the optical approach, reproducing optical behaviours reported in the literature, and analysing optical modifications using Synopsys TracePro. This stage was essential to evaluate building-integration factors such as scaling components to match standardised sizing or improving thermal and fluid dynamic behaviours within geometrical surface areas. Thereafter, the design development was conducted in Lambda LightTools with SolidWorks import compatibility. The linked software provided a platform for parametric integration, whereby material properties, and sizing in SolidWorks, dynamically updated the optical simulation results, and any outputs from the optimisation protocol were recorded in the 3D model. Once a suitable optical profile and modelling parameters for a building-integrated condition were defined, optical efficiency assessments were conducted at various incident angles, followed by optical raytracing of annual hourly solar irradiation between 09:00 and 18:00 at summer, winter, and spring solstices.

Thermal efficiency was assessed using ANSI/ASHRAE testing method standards. The reflective treatments were comparably assessed using spectroreflectometry and bench-scale chemical actinometry experiments and validated with field testing based on the effective increase in solar concentration. The light-transmitting properties reported by the manufacturer were validated with laboratory and field testing to support the daylighting model with detailed spectral transmission data of the glazing systems' interfacial layers in Optics7 software (Lawrence Berkeley National Laboratory). Modelling the glazing properties as Radiance files input into ClimateStudio (Solemma, MIT) for Rhino-3D allowed for preliminary daylighting modelling of variable glazing areas, solar-concentrating reflective properties, and qualitative daylight and solar heat gain modulation through the adjustment of transmission properties. As a system for distributed use in various residential building

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7. Physical experimental prototyping and multiscalar testing in laboratory and bioclimatic field locations, 2022-2023. © Yale Center for Ecosystems + Architecture.

conditions and occupancies, the research used the UNHCR Sphere Standards (2018) for shelter construction as the minimum baseline for building size, consumption demands, and basic services. Therefore, in order to simultaneously ensure sufficient year-round water treatment capacity and thermal performance, the modelling included the design of daylight qualities modulated in a building-scale lighting plan, factoring in window-to-wall ratios, adjacent luminant surfaces, viewfinding, and colour rendering.

System fabrication and testing

The realistic optical performance of a low-cost solar-concentrating building envelope system relied on the mutual concerns for appropriate, affordable manufacture, alongside the optical tolerances required. Therefore, prototyping factored in fidelities typical of mass-manufactured building materials that, unlike precision optics, would need to be produced in higher volumes at reduced fidelity.

The experimentation initially involved two trajectories with optical systems, either using solid transparent dielectric materials to contain how light is refractively shaped, or surface-based reflective optics where the reflectance of light is visually apparent in what otherwise appears as an opaque surface. In each case, optical properties could be programmed into monolithically cast, injection-moulded, extruded, or aggregated assemblies with discrete performance trade-offs in fidelity, cost, and sustainability. Initial studies using total internal reflecting optics with solid dielectric material geometries were produced in a multi-stage process that included CNC milling of moulds in high-density polyurethane (HDPE) and finished by hand-polishing with fine micromesh up to 3000-grit. The polished component was used in the negative casting of silicone moulds, allowing for comparative casting of the optical components in several transparent materials with suitable transmittance properties. Alongside these, iterative optimisation of the optical geometry was rapid-prototyped in Formlab stereolithography (SLA) 3D-printed clear resin that was UV-cured and polished for visual clarity. This process was valuable with initial proof-of-concept testing at the bench-scale under a solar simulator in Arizona, and informed the reflective approach taken with the proposed embodiment that we determined to be most suitable for informal settings.

Challenging the conventional use of high-fidelity aluminium reflectors, which contained high embodied energy and were more difficult to distribute access to, we investigated spectrally selective coating of a lightweight transparent substructure, which forms part of the interlocking building envelope assembly. The approach harnesses the extrusion manufacture of sheet materials or injection-moulding of thermoformable materials to simplify the production of complex optical geometry, using the extruded geometry as a multi-purpose substrate (transparent, lightweight, structural, efficient) for surface applications based on variable requirements by climate and housing type (transmittance-reflectance profile, colour rendering). We assessed several versions of this approach to simultaneously compare the balance between translucency for daylight and reflectivity for adequate solar concentration to raise the water temperature to pasteurisation levels. Prototypes were produced by thermoforming highly transparent polyethylene terephthalate glycol-modified (PETG) sheet materials on which several reflective treatments were tested.

On-site demonstration and evaluation

The experimental work benefited from different physical and methodological environments spanning the US, South Africa, and Central America, each with distinct water challenges, requiring the incorporation of adapted analytic and synthetic experimental exercises across each stage. The ethical and theoretical socio-ecological concerns in water security, governed by ideals of human rights and water purity, informed the consequential development throughout bench, lab, and device-scale field testing, and towards building integration. Laboratory and field testing was conducted in Phoenix, Arizona, and Cape Town, South Africa, both located at ~32º North and South respectively, and an equatorial location in Sololá, Guatemala (~15º N). Since each locale faces issues of water access in the built environment in overlapping and unique ways, performance criteria in each context emphasised effective capacity for water treatment that could overcome seasonal rains and extremes in water contamination, provide bulk water heating to offset boiler costs, and generate energy to supply household essentials such as night lighting and device charging.

Ultimately, the SEWR systemic approach challenges the fundamental premise of modern architecture that enforces boundaries between abiotic and biotic systems. The prior orthodoxy of separating biological systems from building envelopes is rejected in favour of a strategy that fully leverages and activates every available surface and/or volume to synergistically interface with the collection of bioclimatic energy flows, alongside the acceptance and processing of anthropogenic and organismic biological flows. The multivalent system performances, from solar collector efficiency to thermal efficiency, biological disinfection efficiency, visible light transmittance, and solar heat gain, were eco-systemically evaluated across experimental scales and comparisons made between simulated and measured results to improve modelling methods and iteratively improve the design amalgamation of the system criteria. Comprehensive evaluation is thereby also supporting performance extrapolation to urban-level impacts and conducting cost assessments that could have policy-level impacts. Intentionally, therefore, the competitive performances of the system's manifold functionalities and the dynamic remodelling informed by the context perpetuates a productive looseness in how each performance is prioritised and, therefore, short-circuits any default to a single function. In adaptive application settings within a matrix of embodiments, the low-fidelity feedback loops for building systems could effectively be leveraged to balance cost and performance trade-offs across differing renewable materials.

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LIVING MANUFACTURE

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Entropic manufacture

Modern fabrication methods, especially those involving the use of biologically derived materials (which can include plastics, wood, etc.), engage in what might be described as 'entropic manufacture'. Entropic manufacture can be described as making use of 'heat, beat, and treat' to produce materials that are much simpler than their biological origin. In other words, we spend energy to convert highly structured complex materials into simpler, more disordered materials before using more energy to assemble them into composites across often geographically distributed manufacturing chains.

Consider the journey of manufacturing paper. A tree, which is a complex multi-material object – a sophisticated organisation of cellulose, hemicellulose, and lignin finely tuned and organised at the microscopic scale to yield functionally graded materials from the trunk to individual leaves – obtains nutrients and energy from its environment, self-assembles, is responsive, and can produce and distribute information for new trees through its seeds. To make paper, we first undergo a series of disassembly steps, from the felling of the tree to the refinement of pulp through chemical and mechanical degradation, before reforming and pressing it into thin sheets of crushed, beaten, and often bleached, disordered cellulose materials. While paper is functionally more useful for writing a letter than a living tree, this approach, involving building through a process of disassembly, seems counterintuitive.

Entropy is a thermodynamic principle stating that all things lead to disorder and randomness. However, biology temporarily contravenes this law through energetic processes that assemble simple molecules into complex structures at multiple scales, from proteins and cells to multi-cellular organisms and ecosystems. Humans, through our manufactured artefacts, also combat disorder and randomness. Yet many of our manufacturing methods impose disorder and randomness on our materials. We accelerate entropy to give the illusion of order in our constructed environments.

Biological manufacture

What if we fabricated as biology does, starting with simple substrates and assembling complex structures, directing energy to overcome entropy? While there is a long tradition in architecture and design of mimicking nature, we suggest that the only viable option to achieve

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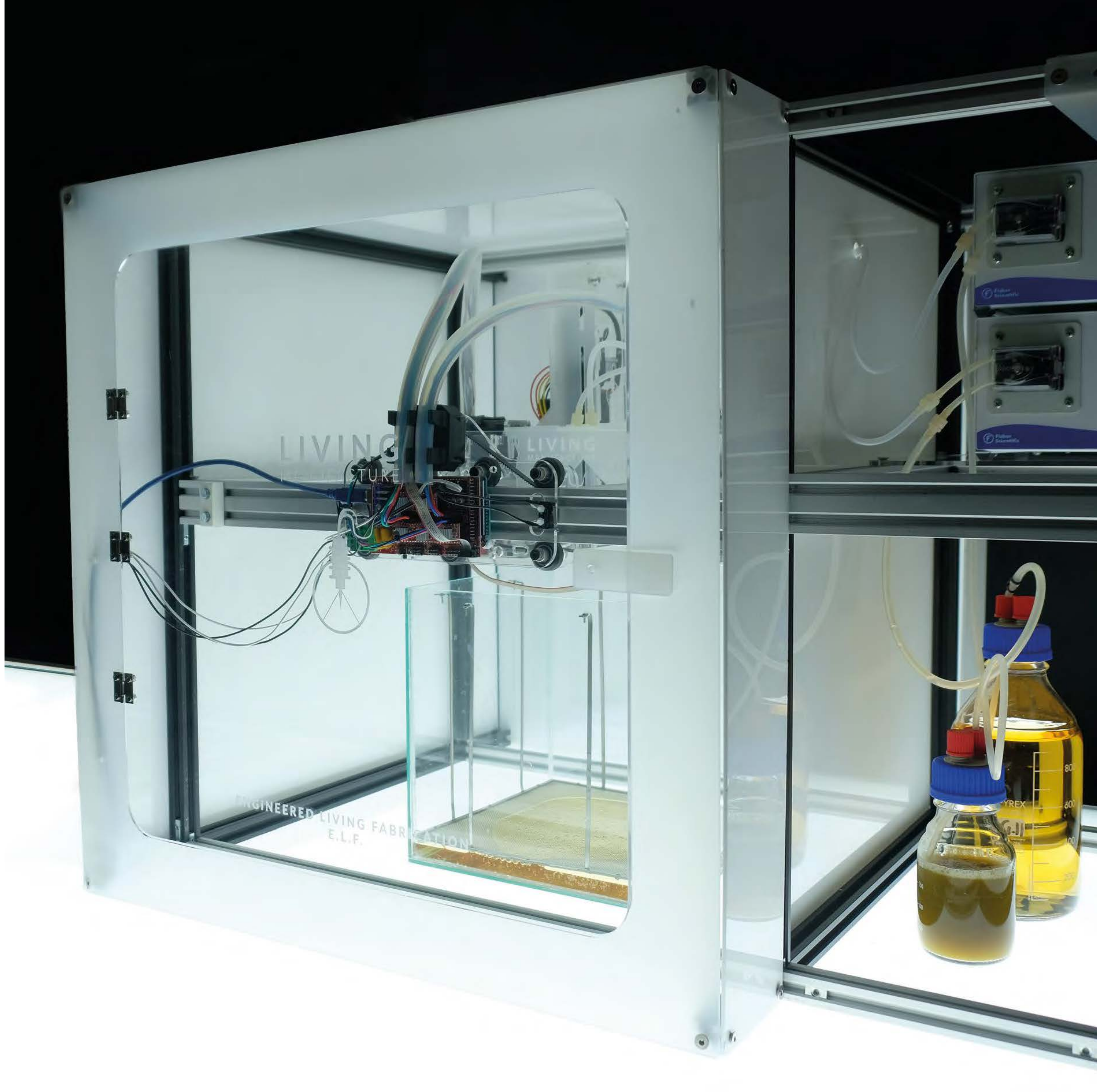

1. Close-up of the Engineered Living Fabricator (ELF) system. © Living Construction Group.

non-entropic manufacture is to utilise biology in the fabrication process. This is not a new idea. Arguably, the origins of biological manufacture lie in agriculture, a technological advancement fundamental to civilisation. However, recent interest in the broad field of biodesign suggests direct engagement with biological fabrication through cultivation practices in the lab and studio, not just the farm or greenhouse. These practices include mycelium-based composites, microbially induced calcite precipitation (MICP), and microbial production of nanocellulose. Working with these materials requires what might be describe as 'close culturing', a type of agriculture that closely controls environmental conditions during growth, often combining moulding processes to shape the material as it forms. These techniques have, so far, yielded products like mycelium bricks (Benjamin, 2018), microbial cement tiles (*Biomason: Revolutionizing Cement with Biotechnology*, 2021), and cellulose leather-like textiles (Choi *et al.*, 2022) – products reminiscent of traditional materials but potentially paving the way for future biological fabrication.

Engineered living materials

The field of engineered living materials (ELMs) is defined '*as engineered materials composed of living cells that form or assemble the material itself and modulate the functional performance of the material postproduction*' (Srubar, 2021, p.274). Informed by advances in materials science and synthetic biology – which apply engineering principles to design living organisms – a stated goal of ELMs is to produce seeds containing a genetic programme that, when planted, would initiate self-assembly into a complex material structure, perhaps even an entire building (Nguyen *et al.*, 2018). Ideally, these materials would not die or become dormant after assembly; they would continue living with capabilities like adaptability, change, self-repair, and additional construction. However, the field of ELMs is in its infancy, and breakthroughs have been modest. Organisms exhibiting complex self-assembly and material fabrication (e.g. plants and mammals) are challenging to work with genetically. Synthetic biology often relies on single-celled microbes like *Bacillus subtilis* and *Escherichia coli*. While complex, they lack innate abilities for intricate morphogenesis or material fabrication. Some projects attempt basic patterning of microbial expression (ELMs) and sensing on a small scale, but we are far from realising the seed-to-construction dream. Some researchers argue that the emphasis on genes as the primary carriers of information is misplaced, and that biological self-assembly occurs within specific environments that influence and template biological development (Dade-Robertson, 2021).

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2. A pellicle of hydrated microbial cellulose showing the layered structure of growth. © Living Construction Group.

3. Pigments containing CBMs dripped onto the surface of the growing cellulose over time showing pigments immobilised within the layers. © Living Construction Group.

Engineered living fabrication (ELF)

One developing approach begins with the principle that, using microbes, we can potentially synthesise materials at scale. These materials can be synthesised by the microbes themselves and self-assembled through processes under direct biological control. However, to organise and pattern these materials, adding complexity – for example, materials that might act like complex composites or exhibit functional gradation – we need to guide the biological processes from 'outside' the biological system. This 'guiding process' could involve physical constraints (e.g. moulding), directly adding materials during the fabrication process, and/or communicating with the microbes through chemical or other types of signals to alter their production via computationally mediated processes. Such a system is referred to as an 'Engineered Living Fabricator' or (ELF) (Fig. 1).

Engineered living fabrication of microbial cellulose

A promising starting point begins with bacterial cellulose (BC), a purer, albeit more disorganised form of microbial cellulose than that found in wood. It is known for properties such as extreme purity, crystallinity, and tensile strength (Klemm *et al.*, 2001). Consequently, its applications span diverse fields, from wound healing (Czaja *et al.*, 2006) and food packaging (Azeredo *et al.*, 2019) to serving as a leather substitute (Lee, 2012). Post-production modifications to BC have yielded composites with specialised functionalities, such as antimicrobial, magnetic, and electroluminescent properties (Legnani *et al.*, 2008).

In the context of an ELF approach, the potential for bulk manufacture means that BC could serve as a primary material. Given the variety of cellulose-based composites found in nature (cellulose is the most abundant biological molecule), it can also act as a 'protomaterial' – a foundational material for new composites, serving as a scaffold or being combined with additives to bestow new functionalities. Its water retention capability further allows it to be the basis for ELMs, creating an environment where other cells can survive and add living capabilities, including, for instance, self-healing, sensing, and environmental adaptability. Recent advancements in ELM research underscore the adaptability of BC. For instance, Gilbert *et al.* (2021) demonstrated BC's modification at a molecular level by co-culturing it with engineered microorganisms.

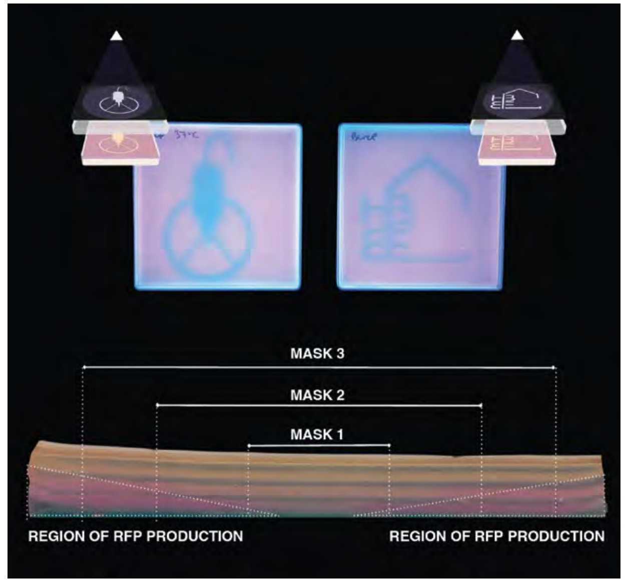
BC fabrication frequently involves producing a pellicle – a hydrated mat – at the air–liquid boundary in a microbial broth filled with glucose and cellulose-producing bacteria. This method limits the cellulose's form, typically resulting in a uniform thin sheet after drying. Efforts to diversify its morphology have altered the growth environment. Techniques such as the 'growing a roll' method, which extracts material from liquid media into a roll and uses a rotating disk bioreactor for consistent nutrient and oxygen distribution (Lin *et al.*, 2014), tend to continue to produce uniform material.

Other cellulose fabrication methods have been proposed, like the printing of scaffolds in tissue engineering. However, our proposition stresses the use of live cells for direct material self-assembly, drawing inspiration from the 'Guided Growth' concept (Zolotovsky, 2017). This approach combines three core technologies, which we describe here as 'Wetware', 'Hardware', and 'Software'.

Wetware

Wetware refers to the biological process of cellulose growth and methods of biological modification. The key construction agent here is *Komagataeibacter xylinus*, which, under the right conditions, including a liquid nutrient broth containing glucose, can produce and extrude cellulose molecule chains. These chains form at the liquid–air interface and create a cellulosic mat (a pellicle) at the rate of about 1mm per day (Fig. 2). We can then modify the growing pellicle through the addition of other biological molecules. Initially, this involves demonstrating the effect of adding proteins such as BslA (a hydrophobic protein from the bacteria *B. subtilis*), which can be applied both as the cellulose is grown and after it has been harvested and dried (Gilmour *et al.*, 2023). This addition not only affects the ability of the cellulose to absorb water but also has been shown to increase the material's strength and fire retardance.

We have also experimented with the pigmentation of growing cellulose. Dripping normal pigments onto the cellulose's surface would allow diffusion throughout the material. However, biological pigment molecules can be engineered to include additions called cellulose binding modules (CBMs), which bind to the cellulose, limiting the diffusion of the pigment and therefore localising its effects. This approach is also relevant to other molecules, including BslA, which can be patterned onto the growing pellicle's surface over time – such that a pattern forms throughout the material's depth (Fig. 3).



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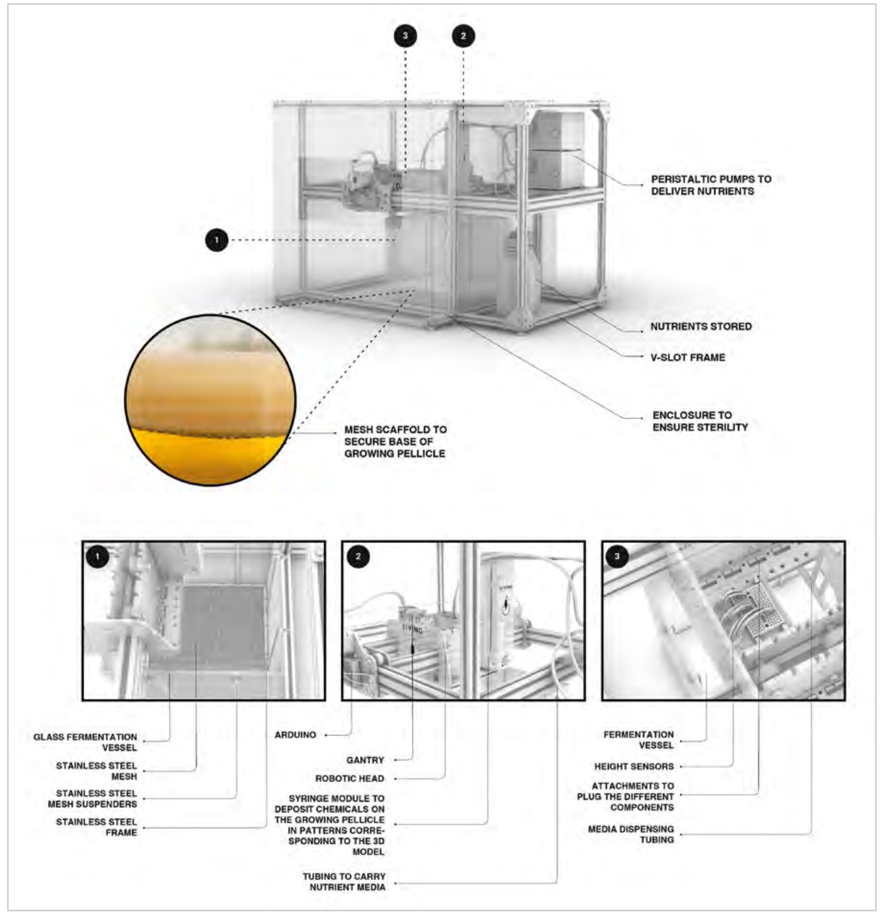
A more sophisticated system would programme the cells themselves to modify the growing cellulose in response to signals. This might involve the investigation of an engineered form of *E. coli*, which is genetically modified to produce a pigment in response to light (known as an optogenetic system). Two systems have been tried: one where pigmentation is activated in response to light, and another, more successful one, where pigments are turned off due to light. This method allows the cellulose surface to be masked with a pattern left in response. Ideally, this could be applied to the growing pellicle's surface, with a mask or a variable projection used to activate pigmentation modification as it grows (Fig. 4). Here, pigmentation can also be viewed as a proxy for other modifications, including, for instance, engineered bacteria capable of producing polymers or modifiers like cellulase, which could modify the material's structural properties in defined spatial patterns if linked to light input.

Hardware

The hardware platform originates from an open-source liquid-handling robot (Faiña, 2020), coordinated through an Arduino interface and executed using Python. It features a V-slot aluminium frame with modular components, facilitating the interchangeability of various dripping and sensing modules onto a motorised gantry system (Fig. 5). There were three main objectives during its development:



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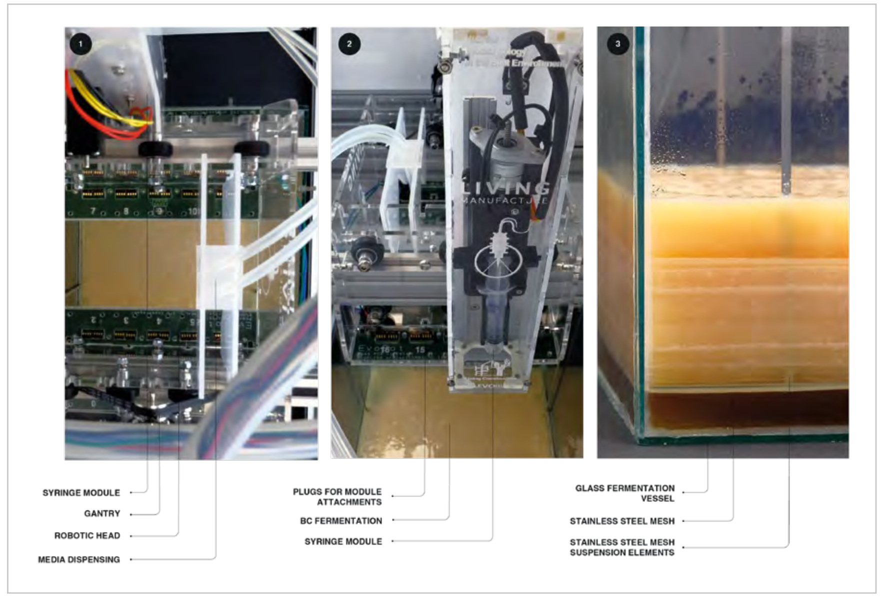
1. Tailored fermentation system for enhanced pellicle growth: A comprehensive analysis of factors affecting pellicle formation was conducted, emphasising maximising growth by optimising nutrient media composition, temperature, and nutrient application techniques. A modified static fermentation method was developed. This technique often results in thin, discrete pellicle layers, which delaminate. To address this, a fermentation vessel was built, which introduces nutrients – primarily glucose – directly onto the BC's surface. For continuous growth, media vessels were connected to a peristaltic pump that dispenses nutrients automatically. The vessel design included a 10l custom-cut glass container. The BC is attached to the vessel's base via a mesh, ensuring continuous pellicle formation as nutrients are steadily introduced and the liquid level rises. The mesh can then be removed, allowing the pellicle to be harvested (Fig. 6).

2. Modular input systems: The hardware development introduced a dual input system: optogenetics and chemical stimuli. Preliminary optogenetic experiments employed a basic masking technique using blue LED lights projected through a card mask.

4. Image showing overhead views of agar plates containing optogenetic bacteria. The plates are masked. The upper images show the results of bacteria where pigmentation has been turned off in response to light and the sections beneath show the effect of increasing the size of the masks as new layers of agar are applied. © Living Construction Group.

5. Three-dimensional renderings to show key elements and details of the ELF platform. © Living Construction Group.



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6. Annotated photographs of key features of the ELF system including (from left to right) the robotic gantry, the fermentation module, and a pellicle anchored to the steel mesh. © Living Construction Group.

7. Prototype of a syringe module for accurate deposition of chemicals into the rowing cellulose matrix. © Living Construction Group.

An automated dripping system of interchangeable 5ml syringe modules was developed. This system uses motorised plungers for accurate chemical and cellular dispensing in varying volumes and concentrations. The modular syringes attach to the motorised gantry, ensuring precise x and y-axis movements, which allows for accurate, programmable spatial control over the chemical stimulus. The system's flexibility also allows for the swapping of modules to accommodate different dripping mechanisms (Figs. 7, 8).

3. Pellicle height sensing and feedback mechanism: This early, yet crucial feedback mechanism through a height-sensing system is able to monitor the height of the pellicle in real time. It can trigger events, such as chemical dispensing, as the pellicle reaches predetermined heights (Fig. 9).

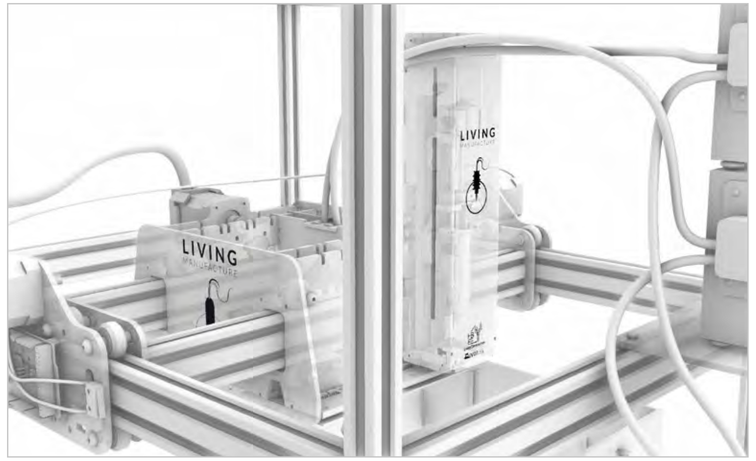
Software

Computational software is deployed to control the process and simulate the results. Unlike 3D printing, where there is a direct correspondence between the three-dimensional form being created and the tool path, this fabrication method is contingent on various factors, including chemical diffusion through the pellicle, bacterial distribution, and growth rate.

A demonstrator of this modelling and simulation software in the Processing programming language was built. The software simulates the diffusion dynamics of chemical triggers and subsequent patterns within an evolving pellicle. The investigation suggested two system scenarios: 1) direct application of a chemical modifier onto the mature pellicle, and 2) incorporation of optogenetically engineered bacteria within the cellulose pellicle, which synthesise a specific chemical in reaction to light. This foundation allows us to plan for the modelling of intricate interactions based on diverse chemical interactions and cellular signalling.

The software takes a 3D model, created in Cinema 4D, as input, and segments it into 40 distinct 100x100px PNG images, each representing a cross-sectional view of the vertical three-dimensional structure. Each pixel's greyscale intensity shows the concentration gradient of the input. Single pixel intensities mimic the dripping action, while groups of pixels represent projected light patterns.

The simulation framework uses a voxel grid structure, sized 100x100x40, where each voxel contains data for a particular chemical concentration within the cellulose matrix. This grid extends incrementally from its base,



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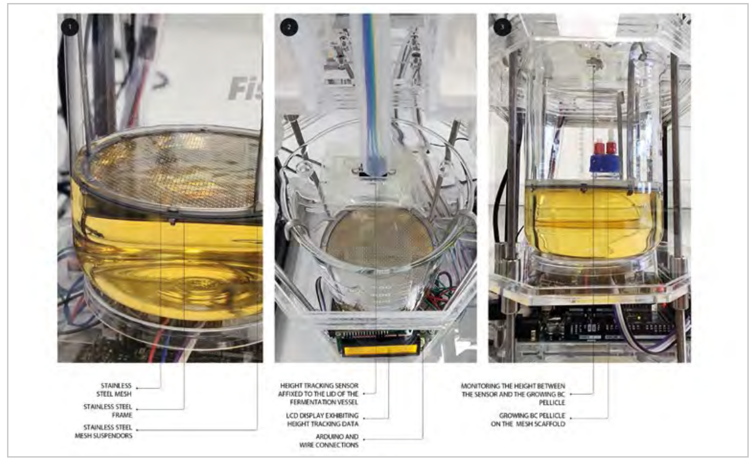

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sourcing data from the associated PNG slice for the pellicle's surface on the z-axis. A range of scenarios were simulated, including two interacting chemical triggers, initiating a subsequent modification process. These are based on 'genetic circuits' typical in synthetic biology, where a cell produces something (a polymer, pigment, etc.) in response to specific chemical signals or concentrations. This system might serve as a foundation for reaction diffusion patterns. The model also comes with a Graphical User Interface (GUI), allowing adjustments to parameters like pellicle growth speed and chemical diffusion rates. Results can then be visualised as a 3D matrix of cubes representing concentrations and patterns within the matrix (Fig. 10). Even though they are abstract and do not yet match real experiments or detailed evaluations of potential material property changes, the results display interesting patterning effects of diffusion systems. Small differences in input chemical amounts were shown to significantly influence the results.

System and framework design

The developments in Wetware, Software, and Hardware help to assess and imagine the broader applications and implications of such a system. While the reported modifications to the cellulose primarily involve pigmentation and hydrophobicity changes, they serve as examples of a fabrication process in which we expand upon the complexity already inherent in biologically synthesised cellulose. By using techniques such as the application of CBMs, the control of molecular interactions combined with macro patterning offers the potential for significantly enhanced fabrication capabilities.

A scalable system can be envisaged where designers can select engineered microbes in a manner similar to choosing printer inks. These modifying bacteria would be tailored to respond to various input types, including different wavelengths of light or distinct chemical signals. These bacteria could produce a diverse array of material outputs, such as the creation of new polymers, minerals, or modifying enzymes like cellulase that can selectively weaken or break down the cellulose. A specification for a material with desired functional properties would be determined, and a simulation would form the foundation for a tool path that controls a multi-input dripping system and projected light patterns. Bacteria that produce cellulose would then be introduced into the fermenter alongside the modifying bacteria. As the pellicle grows, the patterns of chemical signal dripping and light projection onto the material's surface would evolve, leaving behind three-dimensional patterns of material modifications, resulting in a sophisticated three-dimensional composite material (Fig. 11).

Drawing inspiration from wood, such a system may be able to create materials that are flexible in one area and stiff in another. These materials might be water-resistant in parts where they offer weather protection, yet able to absorb and retain water as a cooling strategy, to foster subsequent growth, to promote self-healing of the cellulose matrix, or perhaps even as a habitat for CO_2-absorbing algae. Moreover, such a material would be biodegradable and, at the end of its life, could be enzymatically broken down and repurposed as nourishment for future fabrication processes.

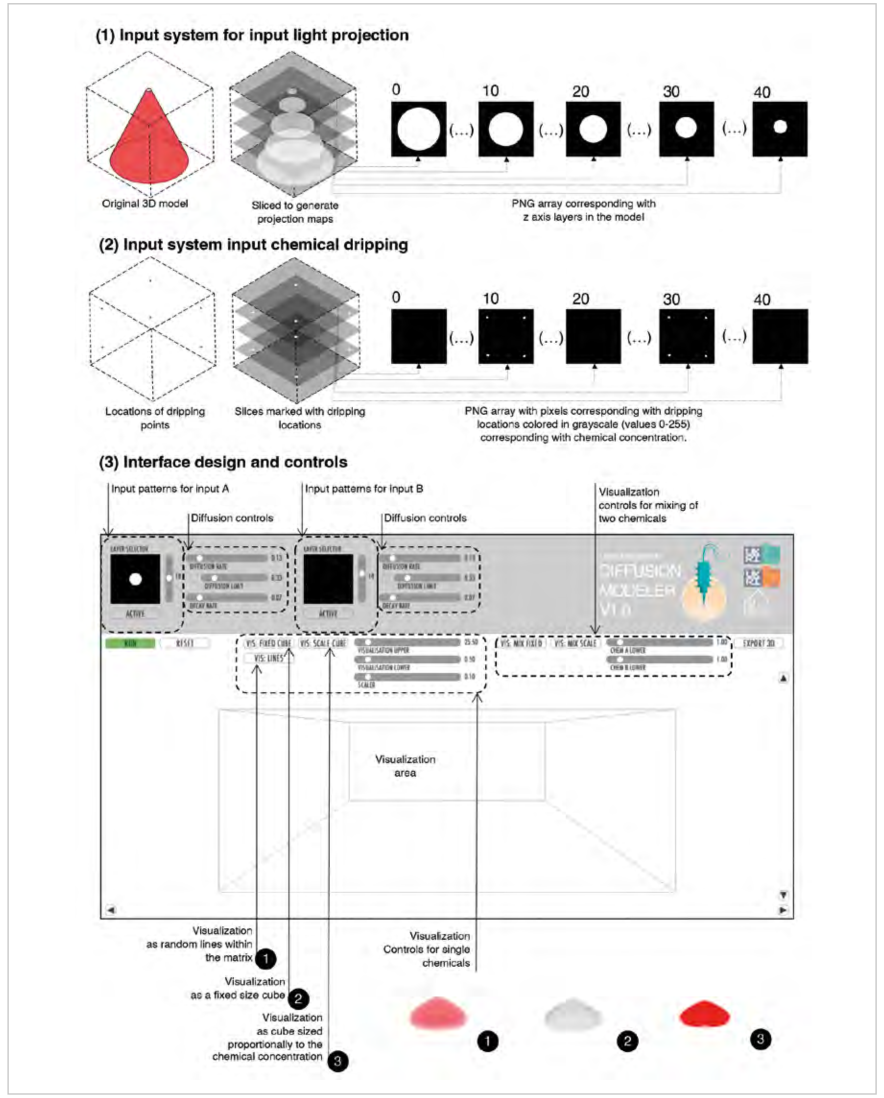
While we are some distance from realising this vision, the ELF lays down foundational principles for such a living fabrication system, opening the door to the possibility of non-entropic manufacturing.

8. 3D rendering of the syringe module attached to the robotic gantry. © Living Construction Group.

9. Annotated photographs of the height-sensing system giving accurate feedback on the height of the pellicle as input into a robotic dropping system. © Living Construction Group.

10. Specification of the software modelling system showing the translation of (1) a 3D model, (2) a series of dripping points into a 3D array, and (3) the graphical user interface for the editing tool showing the main controls visualisation area and examples of outputs. © Living Construction Group.

11. Schematic diagram to show a concept for a manufacturing process involving an ELF system. © Living Construction Group.



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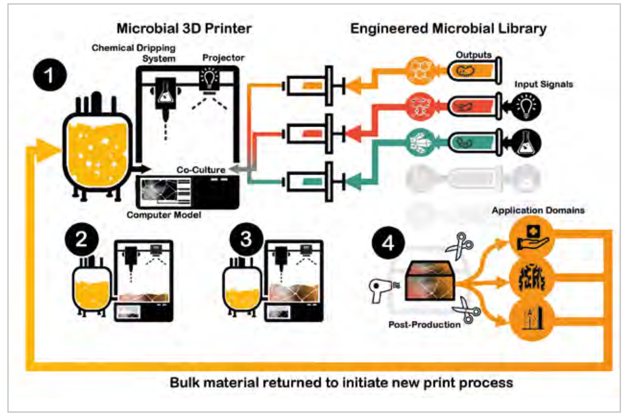

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TERRACOOL URBAN OASIS

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Evaporative cooling (EC) has been used throughout history as a method of natural cooling. However, its implementation within the contemporary built environment is curtailed by water scarcity and the need for specific bioclimatic conditions. This paper introduces *TerraCool*, a novel ceramic evaporative cooling (CEC) system of modular stackable ceramic bricks. Its internal geometry is based on Schwarz-P ('primitive') triply periodic minimal surfaces (TPMS), to maximise surface area of contact between warm air and wet ceramic while minimising water consumption. It examines potential applications of this technology in hot and dry locations, along with how it might integrate into various architectural features, cooling rooms by inducing air circulation. For example, it describes the design and manufacture of an 'urban oasis' for alleviating excessive heat in public spaces, and contends that CEC has the potential to be more widely applied in the built environment than at present.

Context

A rising number of people living in cities are affected by the urban heat island (UHI) effect. The term refers to the phenomenon in which distinct urban enclaves experience significantly higher ambient temperatures than their surrounding areas. The primary cause of this temperature differential lies in the geometry and material composition of urban environments. These features enhance reflection, absorption, and retention of thermal energy from solar radiation.

Urban construction materials featuring darker surfaces absorb thermal radiation. As the surrounding air is heated, it remains trapped by tall buildings that obstruct prevailing winds. The horizontal and vertical geometry of urban structures facilitates the reflection and storage of radiation, while used air from upper levels cannot be replaced with fresh, clean air from above (Gage *et al.*, 2001).

Ceramic materials possess distinct properties, motivating the project's focus on harnessing them to address UHI effects. This led to the formulation of three research questions:

1. How can the EC capability of ceramic materials be geometrically optimised for use in mitigating the effects of urban heat islands?
2. What geometries can enhance the EC effect by

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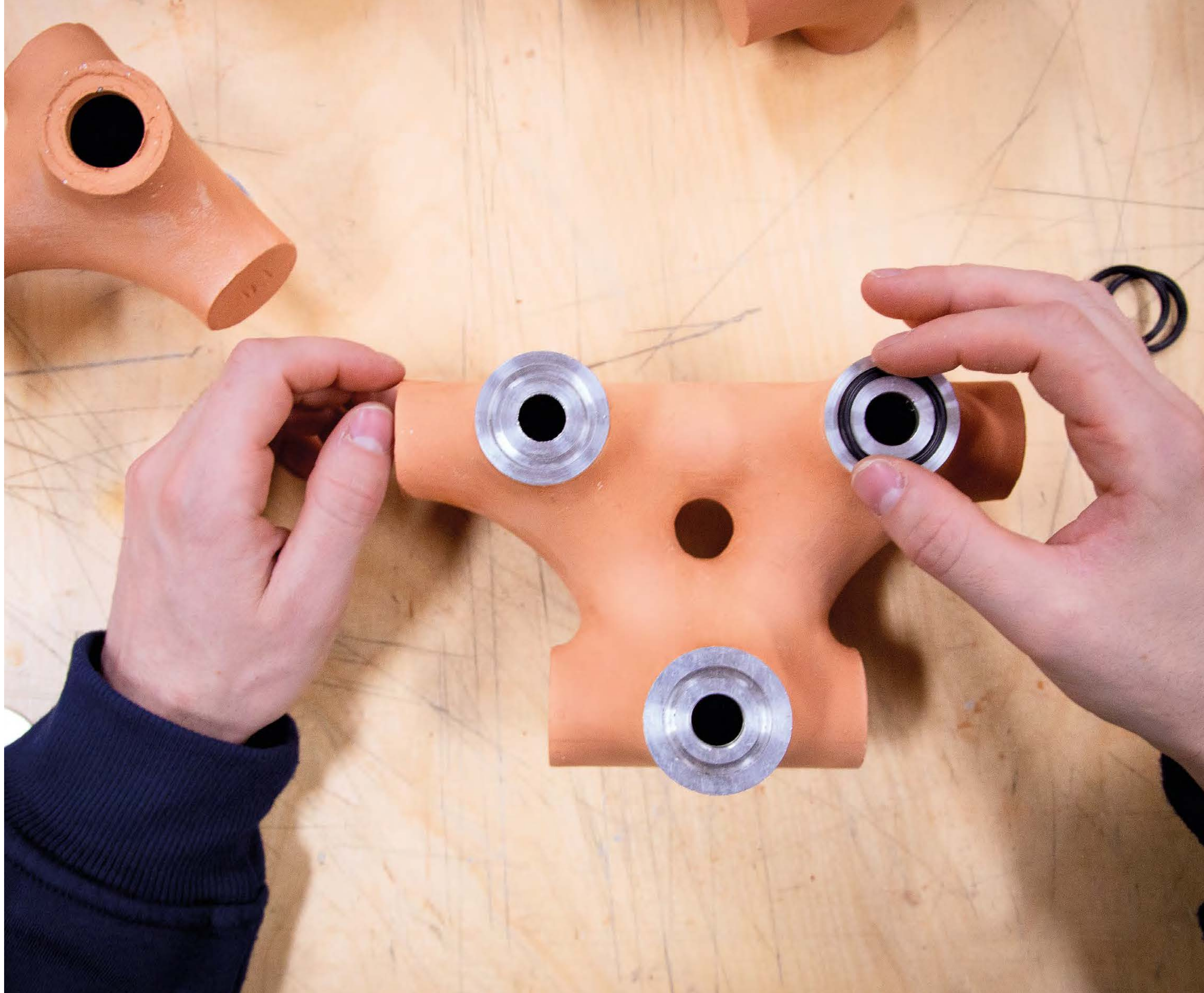


providing more surface area for contact between warm air and wet ceramic?
3. How might CEC elements be incorporated into a modular system that can be tailored to different environmental conditions?

Evaporative cooling

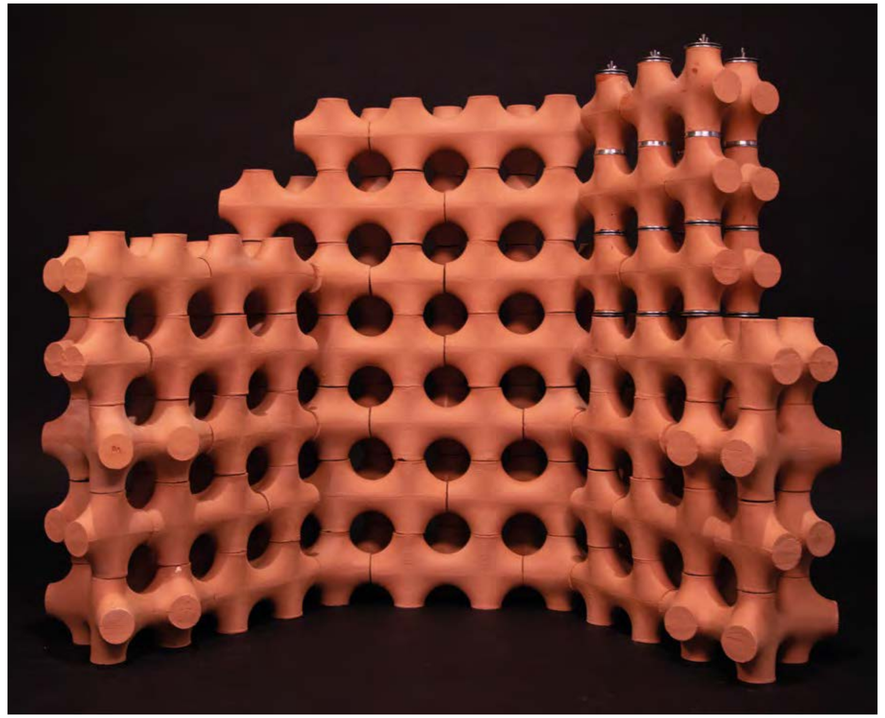
Evaporation uses thermal energy in the air to convert water from liquid to a gaseous state. In this thermodynamic process, sensible heat is transferred from ambient air and surfaces to water, raising the moisture content in the air while reducing its temperature. This phenomenon has been employed throughout history to naturally cool buildings, public spaces, and drinking water. Because of their porous structure, ceramic materials are uniquely suited to EC applications. The porous structure of fired terracotta allows water to permeate the surface of the material. Water seeps through the pores to the surface, where it evaporates, cooling the ambient air (Elfatih *et al.*, 2003). Ceramics can passively siphon water when placed in a pond, even if there is no pump. It can provide cooling for extended periods because of this efficient capillary ability. Ceramic pipe placed in a 10cm water bath can draw water about 1m upwards depending on the pipe diameter (He and Hoyano, 2010).

Historical and modern passive cooling precedents

CEC is an old technology that is widely employed in the arid regions of the Middle East; the Muscatese windows of Oman are a well-known example. Passive cooling systems such as *malqafs* and *salsabils* have been documented throughout southern Spain, North Africa, the Middle East, and Northern India (Fathy, 1986). The ice houses of Iran used similar methods to preserve ice in the desert and were the source of the first ice cream in history (Ford *et al.*, 2020).

As the climate crisis has led to renewed interest in these ancient cooling technologies, a growing number of studies have sought to integrate CEC systems into building skins. Casa Patio 2.12 has a façade featuring a capillary irrigation system that gives sustained moisture to ceramic modules that are attached to the building's walls in such a way that a hollow chamber is formed (Bechthold *et al.*, 2015). Evaporation cools the air in the cavity, which is then drawn through a gap in the base of the walls into the building interior with the help of a solar chimney.

A different approach to irrigation was developed for the Sony City Osaki building in Tokyo, which uses more than 9500 porous ceramic pipes filled with rainwater, creating a cooling envelope around the building. In tests conducted



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on a prototype under conditions resembling the actual site, the ceramic solution exhibited significant benefits. Specifically, the wet ceramic system resulted in a surface temperature that was 5–9°C lower. Computational fluid dynamics (CFD) simulations performed at the scale of the real building predicted a 10°C reduction in surface temperature, a 1–2°C decrease in temperature near the glass enclosure, and a 2°C drop in the vicinity of the building (Bechthold *et al.*, 2015).

The Spanish Pavilion in Zaragoza uses porous terracotta columns with internal spray nozzles for continuous surface moistening, enhancing evaporation and venting cooled air into occupied areas. Other projects like Cold Spot, E-cooler, and Evapcool offer modular elements for evaporative cooling, showcasing the potential for standalone CEC components in various applications, each with unique characteristics and limitations (Bechthold *et al.*, 2015).

Following a review of existing state-of-the-art CEC, we identified the need for a design solution that could improve the performance of a CEC system through geometrically optimised components minimising water usage and irrigation points. If filtration can be implemented, there is the prospect of delivering irrigation from local greywater sources. Therefore, the ultimate

1. First set of brick-metal top connection and O-ring placements. Shrinkage after firing requires careful consideration for these connections.

2. *TerraCool* presented at The Bartlett's FIFTEEN show, December 2022.

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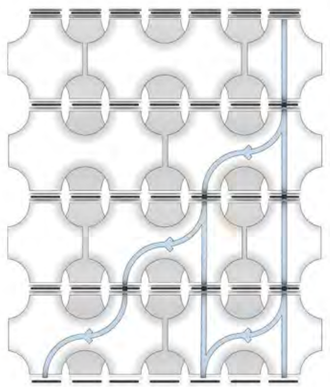

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3. *TerraCool* bricks close-up. Flashing aluminium plates hold O-rings for a watertight seal.

4. Plaster mould making with CNC-machined blocks. Plywood frames joined with 90° angle, ready to disassemble in approximately one hour.

5. *TerraCool* bricks are stacked in staggered order as in traditional bricklaying for strength and desired water flow. When fed from a few locations at the top, water travels through the entire system.

objective of this project is to achieve passive cooling via design intelligence, mitigating reliance upon active cooling systems.

Form study: Geometric objectives

Since CEC systems function by introducing moisture into the air, expanded contact between damp ceramic surfaces and air promotes more effective evaporation. The ideal design of a CEC module would have the highest possible ratio of surface area to internal volume. The geometry should have an aerodynamic form to allow unrestricted airflow across its surface, minimise water consumption, and be able to withstand compressive and hydrostatic loads when modules are stacked.

A class of mathematical surfaces that locally minimise surface area for a given boundary known as triply periodic minimal surface (TPMS) have attracted considerable research interest because they have shown better mechanical performance, mass transfer, and thermal conductivity than conventional and strut-based structures in a range of cooling applications.

Notwithstanding their widespread use as a passive heat exchanger, TPMS have not been studied in the context of architectural CEC systems before (Peng *et al.*, 2019).

We hypothesise that the ability to manufacture CEC modules with TPMS geometry could significantly increase the efficacy of passive cooling systems for building ventilation.

Minimal surfaces are characterised by having the smallest area between their edge boundaries. TPMS are a subset of these, which can be infinitely repeated in three dimensions, making them suitable for modular elements used in structural stacking. TPMS offer a high surface area-to-volume ratio, facilitating efficient heat exchange within their channels. This is particularly advantageous for evaporation, maximising contact between wet surfaces and the surrounding air.

TPMS effectively divide a 3D space into interconnected channels, allowing fluids with varying temperatures to flow through and exchange heat. These surfaces have a mean curvature of zero at any point, ensuring a smooth geometry that promotes unhindered flow without resistance.

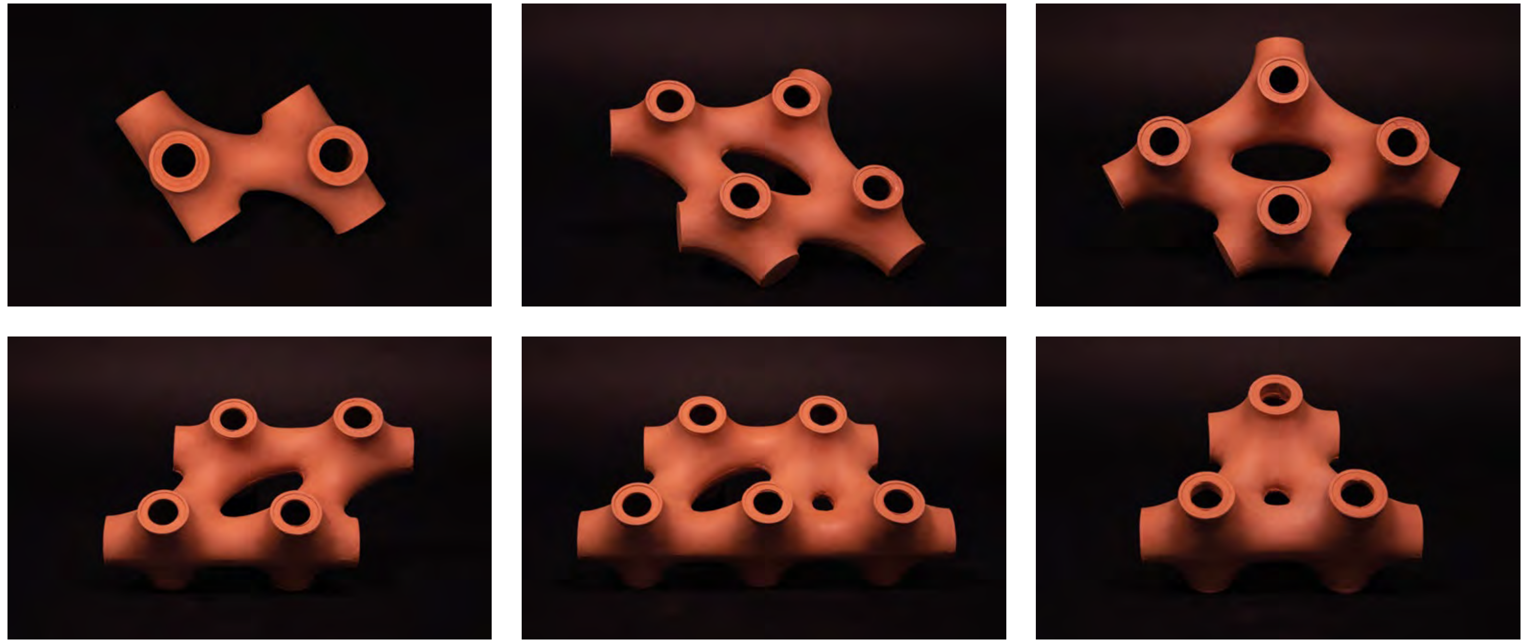
Aerodynamic shapes have been found to enhance evaporation in ceramic evaporators by facilitating unrestricted airflow and ventilation through the ceramic elements (Chilton *et al.*, 2017).

A parametric approach to design and manufacture

As a result of its increased ratio of surface area to internal volume, minimal surfaces have the potential to outperform existing CEC systems. However, their complex geometry makes it difficult to produce these forms in a ceramic material. Additive manufacturing is an established technique for producing lattice structures in ceramic materials. However, the cost and time required to manufacture CEC modules for a building façade would be prohibitive.

We identified Schwarz-P surfaces – one of the minimal surfaces introduced by H.A. Schwarz in 1880 – as being suitable for adaptation to 'slip casting'. Schwarz-P geometry features six equidistant arms, protruding outwards from the centre in the x, y, and z axes. The Schwarz-P geometry can be infinitely stacked in the x and y axes and its surface geometry can be divided in a central plane, making it castable using a two-part mould.

A Grasshopper script was created to generate curved arcs forming a surface reminiscent of a Schwarz-P minimal surface. This surface can accommodate any number of arms at varying angles. These curves were then lofted, creating smooth surfaces. To generate these curves, the script utilises Bézier spans and interpolated curves,



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based on input parameters that define the primary curves, ensuring seamless connections between the surfaces along parting lines (Fig. 7).

These individual units can be combined similarly to the Schwarz-P geometry, allowing for versatile configurations. By altering the number and arrangement of arms, various sub-elements are generated and combined to create different brick forms. A prototype brick was designed using two sub-elements: a central six-sided element surrounded by six four-sided elements. This resulted in a larger six-sided brick suitable for vertical stacking to create pillars (Fig. 6).

For the initial manufacturing of these bricks, half of the geometry was machined from stock material and affixed to a wooden base. Plaster was used to create a mould from this positive. A pair of moulds were used to cast each piece. This manufacturing method was well suited to the geometry of the brick, due to its planar symmetry.

End details were designed to interlock bricks, incorporating grooves for O-rings creating watertight seals. This configuration is particularly useful in applications where evaporative columns cool semi-open spaces while allowing air and pedestrians to move freely. To maintain a consistent water supply throughout the structure, the blocks feature alternating holes that evenly distribute water. If the water source is insufficient to fill the entire structure, the capped bottoms ensure that each brick maintains a minimum level, much like a champagne tower (Fig. 7). Three potential use cases were envisioned for *TerraCool*, with a focus on vertical columns and linear arrays selected for further development.

Modular iteration for versatile applications

A second prototype was developed to create brick typologies suitable for both horizontal and vertical stacking, ideal for creating screens or façades (Fig. 8). These bricks are larger, have more combinational variations, and depart from the planar symmetry of the initial brick. To efficiently manufacture them, a new methodology was devised.

All modules were fabricated using a 4-axis machining operation. By flipping the stock material, all surfaces of the geometry were machined, starting with roughing passes using square up-cut tools, followed by a finishing pass using a ball nose tool to achieve a smooth surface (Fig. 10). After machining, these units are joined forming the desired geometry of each brick. These joined modules are used as positives to cast plaster moulds. Four types of polyurethane foam blocks are machined, creating the brick positives.

To create plaster moulds, polyurethane parts are joined and partially submerged in a clay bed, with walls clamped to the edges. Plaster is poured into the frame. Once the plaster sets, the clay bed is removed, and the mould is flipped to be used as the positive. Funnels are placed into the tops of each brick, which, when removed, leaves a funnel shape in the plaster into which the slip is poured (Fig. 11). This approach makes it possible to cast larger, complex bricks without the need to individually machine each entire form. The machined positives can be reconfigured to produce a range of variations. The caps for these bricks, designed to receive O-rings, are machined separately from aluminium and slotted into the positives before casting. The shrinkage of the clay during drying and firing means that achieving accurate grooves in ceramic is challenging. Transferring these details to aluminium ensures precise tolerances.

Brick elements are interconnected using O-rings and threaded rods passing through holes in the elements (Fig. 12). Threaded caps at the tops and bottoms are tightly secured, compressing the O-rings between mating faces forming watertight seals. Since bricks are not adhered to each other, the structure can be disassembled for redeployment or maintenance, including the replacement of damaged components.

6. Examples of mathematical surfaces that locally minimise surface area for a given boundary are known as triply periodic minimal surface.

7. 4-axis CNC machining of polyurethane block positives on HAAS machine. Denser products are used as block material to achieve smoother surfaces.

8. Diagram mapping the steps from inputs to create Grasshopper surfaces to the first iteration of *TerraCool* bricks.

Applicability

Arid regions, where EC works best, face challenges in water scarcity. To implement EC effectively, aspects like local bioclimatic conditions, urban layout, and water sources must be carefully assessed. Historical buildings hold valuable examples of sophisticated passive systems combining multiple cooling mechanisms including evaporation, transpiration, convection, and the variable buoyancy of air based on temperature differences. Greywater, which includes wastewater from sources like baths, showers, and sinks, presents a viable potential resource for EC systems.

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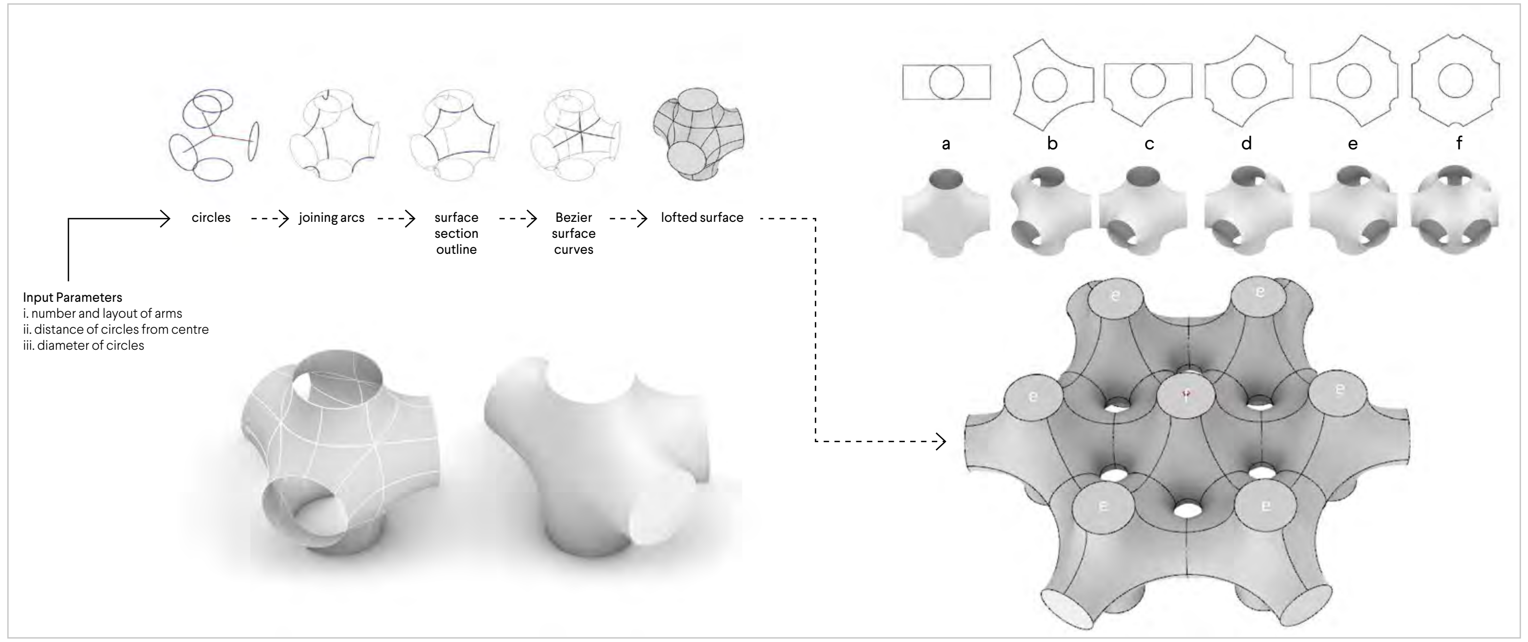
Direct EC has climatic limitations; its cooling effect is limited to the immediate surroundings. Integrated passive cooling strategies offer a way to expand its applicability. These strategies leverage the relative temperature difference of air cooled by evaporation to induce changes in air density,



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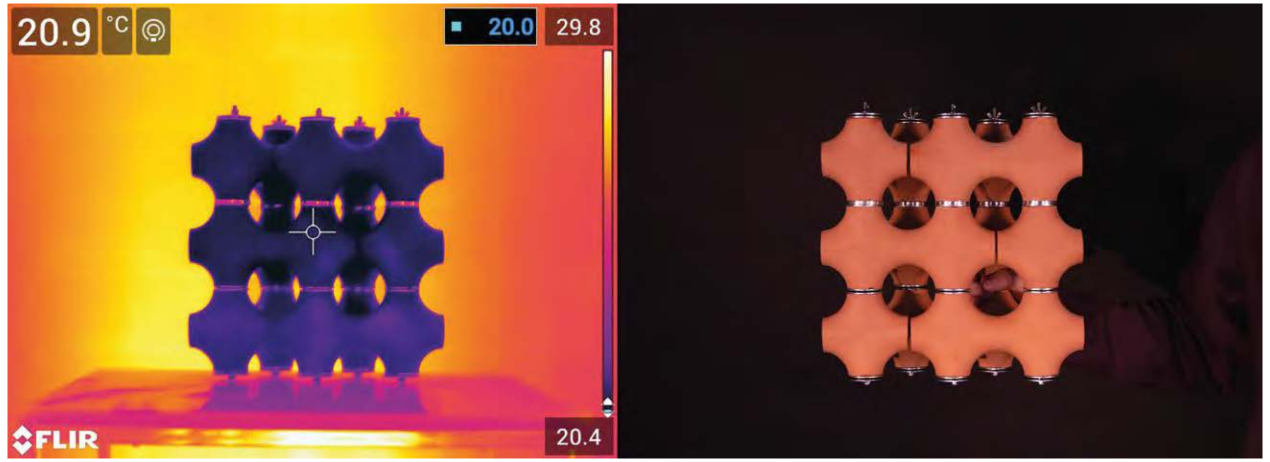

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simulating airflow. Ventilation strategies are vital for passive cooling both in indoor spaces and at the urban scale.

Cooling interiors

Downdraft airflow systems typically rely on a source of cooler air to drive airflow. Examples include central atriums, shafts, or perimeter towers equipped with cooling sources to generate downdraft currents (Chilton, Guillott, and Vallejo, 2017). *TerraCool* presents a promising cooling source for these systems; its sealed terracotta system poses fewer health risks than alternative sources such as misting systems, shower towers, and cellulose matrix pads, which directly expose water to the air, risking microbacterial contamination.

In this configuration, *TerraCool* bricks are strategically placed near a building's upper levels, to harness the stack effect. Warm indoor air ascends and exits through lower-level openings, creating a negative pressure zone. This induces the intake of cooler outdoor air, which undergoes further cooling through contact with *TerraCool* surfaces before descending to lower levels, cooling and ventilating the interior (Fig. 9).

TerraCool can be deployed within a wall cavity as a column of porous ceramic evaporators. Adjustable openings at the top of the exterior wall allow outdoor air to enter the cavity. As this air passes over the *TerraCool* ceramic surfaces, it undergoes evaporative cooling. The cooled air naturally descends to the bottom of the cavity, where it is drawn into the building's interior by negative buoyancy forces. This can be paired with a solar chimney, further enhancing removal of warm air, as demonstrated in the Patio 2.12 building.

Creating an urban oasis

A possible use for *TerraCool* is in public areas of cities, where it would serve as the primary element of an urban refuge, like an oasis in the desert. A proposal was developed that makes use of treated greywater obtained from the water systems of nearby buildings. It minimises cooling loss by being situated within an enclosed site, encircled by buildings on three sides and protected by an entry screen on the fourth (Fig. 15). The evaporator and entry screen work together, creating a calm, cool environment in an urban pocket park that resembles a *stepwell* or *summer room*. The system is powered by photovoltaic panels mounted above the entry screen and is managed by sensors for water control. A waterproof membrane ensures a closed system for the plantation roots, preventing any loss of treated greywater.
An integrated plantation using excess water from a surge tank can provide shade and partial enclosure for an external screen, promoting evapo-transpiration and enhancing the urban oasis, while additional ceramic materials arranged as a pond can facilitate water movement and cooling, thanks to their capillary absorption capacity, even in the absence of a water supply (He and Hoyano, 2010).

Conclusion

The use of CEC systems in the built environment today is constrained by issues of water consumption and the requirement for specific bioclimatic conditions which restricts their application to a finite number of geographical regions. *TerraCool* contributes to the advancement of EC as a means of mitigating urban heat islands through two significant innovations: surface geometry optimisation based on TPMS and the manufacturability of such geometries using a modular slip-cast mould system. This approach achieves enhanced cooling performance and provides a range of module installation possibilities for use in building envelopes and public spaces.

TerraCool is the first system of its kind to make the optimisation of surface area a defining design principle. Whereas TPMS structures are known to be difficult to manufacture other than through advanced methods such as additive manufacturing, this project has demonstrated the possibility of manufacturing modules with Schwarz-P typology through slip casting. We anticipate this use of accessible materials and production methods will contribute towards the acceptance of CEC as a viable passive cooling technology, enabling it to become more widely applied in the built environment than it presently is.

9. Thermal image from rudimentary tests. A kiln testing was undertaken, and cooling was considerably faster with the structure. A 12-degree temperature drop is observed with the prototype, nine times faster than without the prototype.

10. Diagram illustrating the entire process of slip-casting *TerraCool* bricks.

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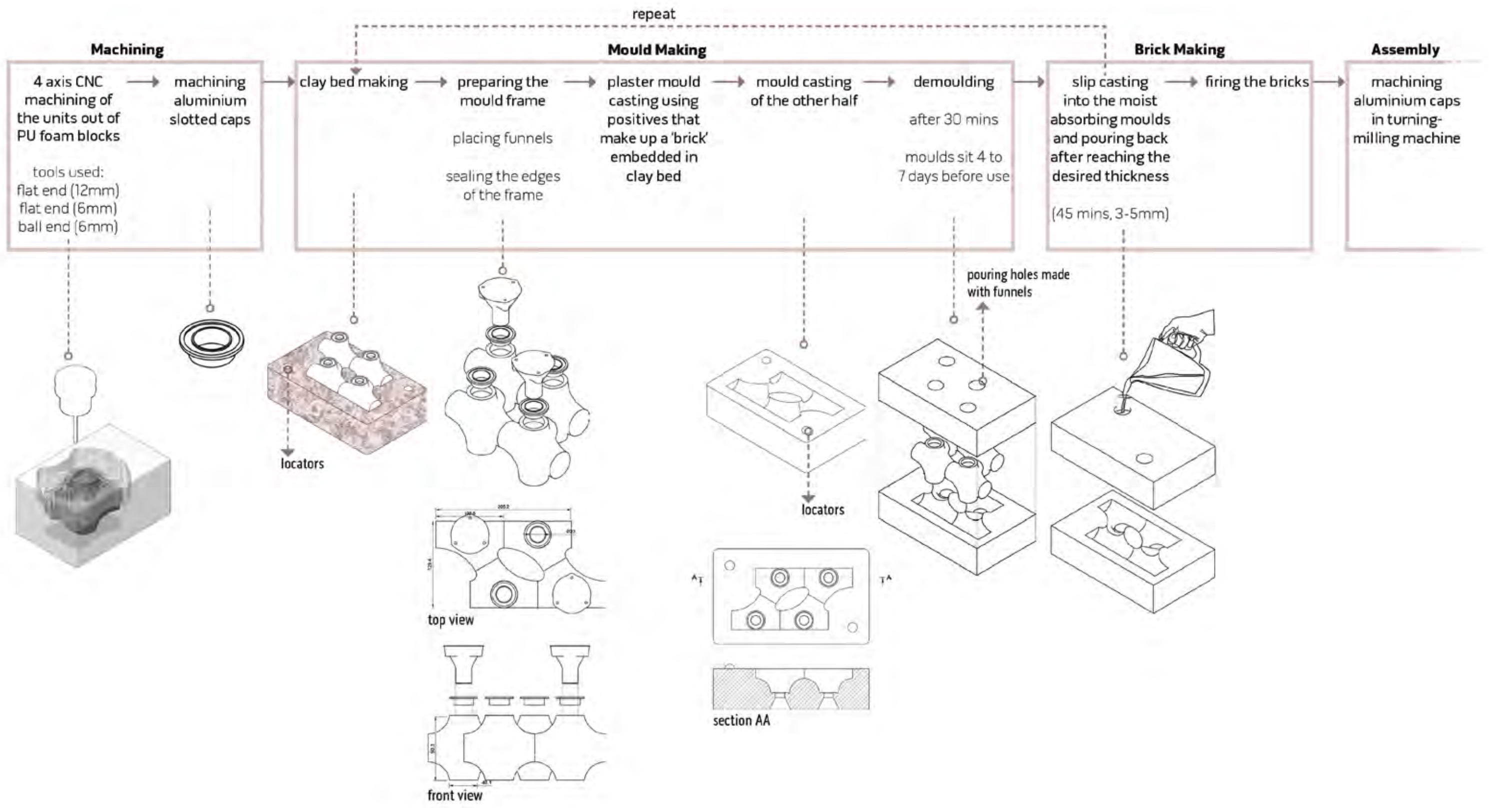

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LONG RANGE
INTRINSIC ACOUSTIC PERFORMANCE

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ZACKERY BELANGER
ARCGEOMETER

Long Range reshapes glass at a variety of scales to invoke gradients of acoustic behaviour: reflective, diffusive, absorptive, and transmissive. The intention is to calibrate material geometry and sound to one another intrinsically within a system of enclosure and light transmission. As such, the transformation of the form of the architectural surface eliminates the need for secondary acoustic or visual material additions, and inherently improves the comfort and quality of the space. A close coordination between the process of form-making and emergent acoustic performance establishes a material system and fabrication method that allows spaces to be tuned through geometric variation (Fig. 2). By using glass, a material overwhelmingly deployed for flat planes in architectural enclosures, *Long Range* systematically coordinates acoustic and optical performance to demonstrate that glass can be more than an invisible barrier with detrimental acoustical qualities. *Long Range* reduces waste both within the fabrication process, through the elimination of moulds and subtractive form-making processes, and within the final assembly, by combining the typically discrete elements of enclosure, light passage, and acoustic dissipation into a single material system.

Acoustic disconnect

In practice, the acoustic experience of a space is often neglected in favour of the visual. Acoustic design is usually limited to appliqué, to the 'treatment' of a space in hindsight, and only prompted by a specific request or a crisis of comfort. Acoustic treatment rose to prominence in the 20th century in response to several forces, notably the removal of ornamentation and the rise of audio technology. Three-dimensional ornament diffuses sound energy, and modernism's unapologetic erasure of it caused sound to sustain for longer than it otherwise had, producing loud and uncomfortable spaces. Even the stark premodern surfaces were not entirely flat, due to the uniqueness of stone assemblies, the subtle variations of hand-applied plaster, the fine porosity of wood, and the inherent distortions within plates of glass. Inherently, these material and geometric qualities of a space define its acoustic performance. Twentieth-century fabrication technology produced flattened surfaces, which invited echo. Engineered acoustic surfaces were developed to absorb sound with a minimal visual impact – the sonic descendants of the ornamentation that preceded them. It is a matter of concern that the addition of acoustic treatment within a space brings with it

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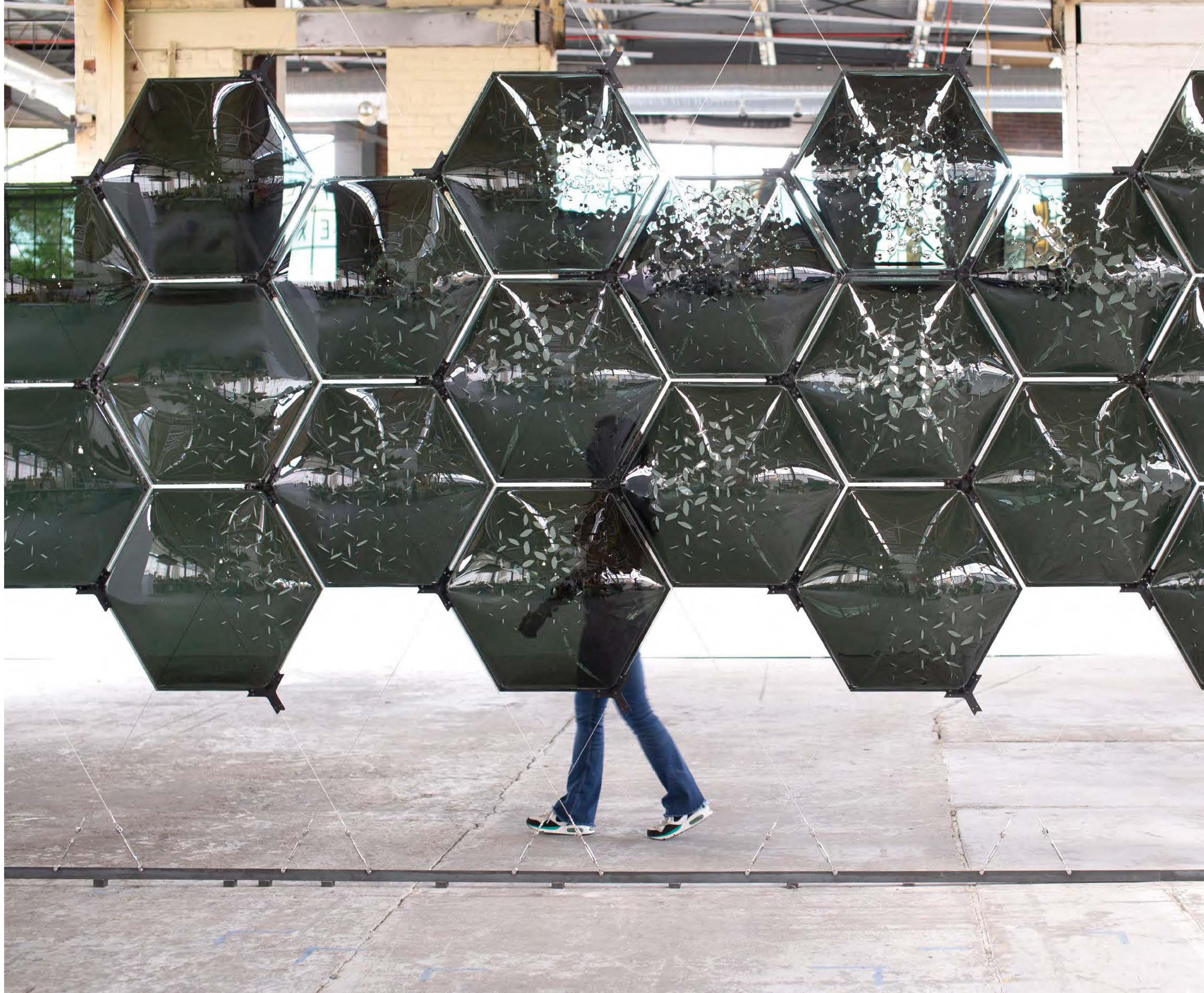

additional material and energy use and ultimately more waste, all of which is most often not intrinsically coordinated with the other designed elements of the space. Current approaches in acoustics only add to the complex and resource-dependent material layering of conventional building systems. The sonic performance of a space would be better understood and accounted for as an integral part of the design, as opposed to an afterthought or added component. *Long Range* is an intentional step towards a recalibration of the visual and the sonic, a reintegration of acoustic performance into enclosures via shaping of the surfaces themselves, and a recollection of the inherent and intentional shaping of material more common in the past.

Sonic and optical gradients

Long Range is made with Guardian Glass 4mm PrivaGuard®, a glass typically sourced for tinted automobile windows. This very dark green glass reflects the light of its surroundings, creating a strong visual register of the relative curvature or flatness as seen through optical distortion. In contrast to optically clear glass, which is intended to be seen through, the formal changes across *Long Range* invoke visual properties that also inform acoustic design decisions. Visual attributes occur at various scales that matter to sound, including distortions of curvature between concavity and convexity, compounding effects of perforations as seen through multiple layers, and minute details of surface variations in the openings (Figs. 3, 4). Further, even the most subtle degree of curvature has a remarkable visual difference from an entirely flat pane (Fig. 5). While colour and the optical transmission rating of the glass have no bearing on the acoustic performance of the system, these optical attributes provide a means to visually understand the geometric variations within the system that do matter to sound. Connecting the details and shaping the glass to light and sound energy leads to an apparent correlation between glass formation and acoustic behaviour.

Long Range is composed of slumped glass panes arranged in a double layer. The panes are paired face-to-face along their edges to make glass bubbles of varying properties (Fig. 6). Moving from flat panels at one end to progressively slumped and perforated panels, *Long Range* culminates in deeply curved panels with porous openings (Fig. 7). The flat end primarily exhibits acoustic reflection, the centre diffusion, and the severe end absorption. Transmission, which is a lesser-appreciated acoustic behaviour that emerges from the degradation of the enclosure itself, also increases along its length. Internal volume quantities are achieved by carefully pairing together two panels, noting that the cavity this creates can be controlled through the depth of the sag as well as the orientation of concave or convex surface curvature. In other words, each pair of panels can create multiple internal volumes if either of the two panels is flipped to switch it from concave to convex. The hexagonal pattern further allows rotation of each panel to vary perforation alignment across a bubble

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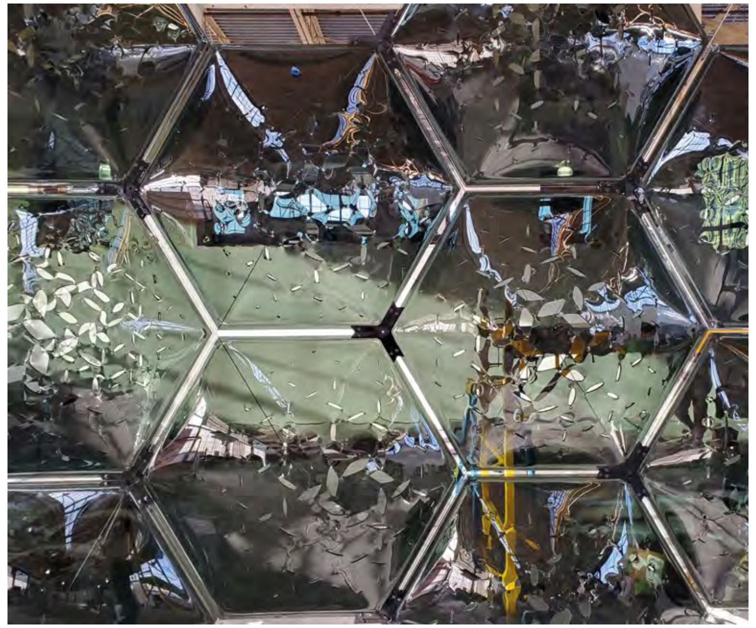
1. The anticipated acoustic behaviours across *Long Range* are best understood as gradients and concentrations within different zones of the wall. Severity and direction of slumps, as well as location and quantity of perforations, determine the degree to which sound is altered by reflection, diffusion, absorption, or transmission. © Catie Newell, University of Michigan.

2. *Long Range* uses glass to calibrate geometry and sound through surface modification using a range of surface curvatures, openings, and pocketed volumes to access behaviours along the acoustic spectrum. © Zackery Belanger, Arcgeometer.

3. Detail view of compounding optical and acoustical effects between and across two layers of glass. © Zackery Belanger, Arcgeometer.

4. Alignment and misalignment of openings in glass panes produced by rotation of the hexagonal base within a double-layer system. © Catie Newell, University of Michigan.

5. Variation in optical reflection relative to concave and convex curvature, or flatness. © Catie Newell, University of Michigan.



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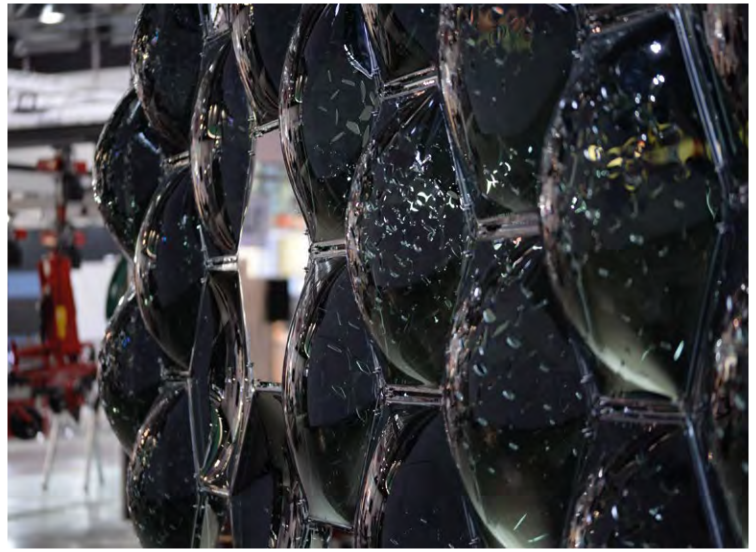

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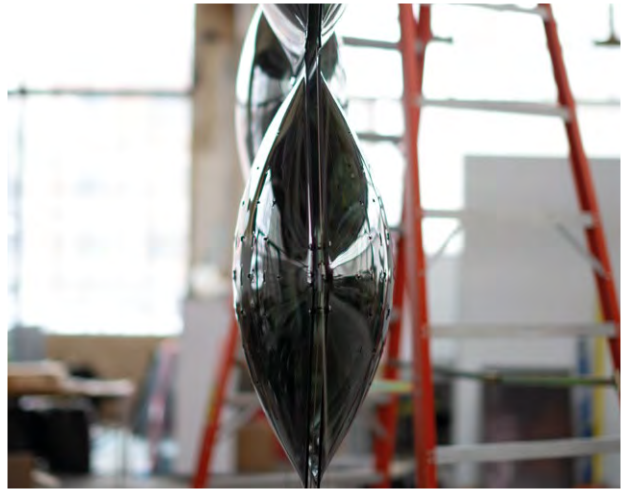
or relative to neighbouring panels, as well as the interchangeability of any panel along the entire system. The panels aggregate into a single visual and acoustic surface, all parts of which exhibit varying degrees of all four traditional categories of acoustic behaviour, coalescing them into an uninterrupted acoustic gradient (Fig. 1). A key initiative of the project is to understand the entire assembly as a single surface with multiple, spatially defined functions, both internal and external to the surface geometries (Newell *et al.*, 2022).

Moving through the acoustic spectrum

Acoustic behaviour was tuned for each panel during production by targeting specific output geometries within a range of control (Fig. 15). Panels begin as hexagonal planes – acoustically reflective blanks – which can optionally be perforated with a modified auxetic pattern (Fig. 8). These blanks are suspended within a frame designed and constructed to support and fix the perimeter of each piece (Fig. 9). A repeatable edge condition is thus produced for a range of slump depths while eliminating the need for hard moulds, which would be numerous and limit shape to discrete possibilities. This catenary-slumping method induces a continuous range of panel curvature possibilities through heating and self-weight, and the auxetic perforations allow the sag distance and curvature to correspond to greater openings within the surface of the glass. The typical behaviour of a cut pattern is to contract perpendicularly to the direction of forces when stretched, exhibiting a positive Poisson's ratio. Instead, auxetic patterns demonstrate a negative Poisson's ratio, expanding perpendicularly to the direction of the force when stretched. In this manner, the material unwinds within the original plane of the surface as it sags, creating openings from material displacement controlled through perforation size, shape, quantity, and density (Fig. 10). Further nuances in the curvature of each panel and the location of the openings are determined by augmenting the auxetic pattern and its placement within the reflective blank (Belanger *et al.*, 2018) (Fig. 11).

The most challenging acoustic realm for non-porous glass is absorption. Acoustic products usually rely on deeply porous surfaces, which are so complex in shape that they maximise the conversion of sound energy into heat. These are the common acoustic panels of felt, foam, and fibres that are sold as additive products. *Long Range* targets a different range of scales to explore more visually interesting shaping, while still aiming to incorporate absorption. The slumping process and double layer give access to a significant range of effective surface depths, and the opportunity to create cavities in some modules



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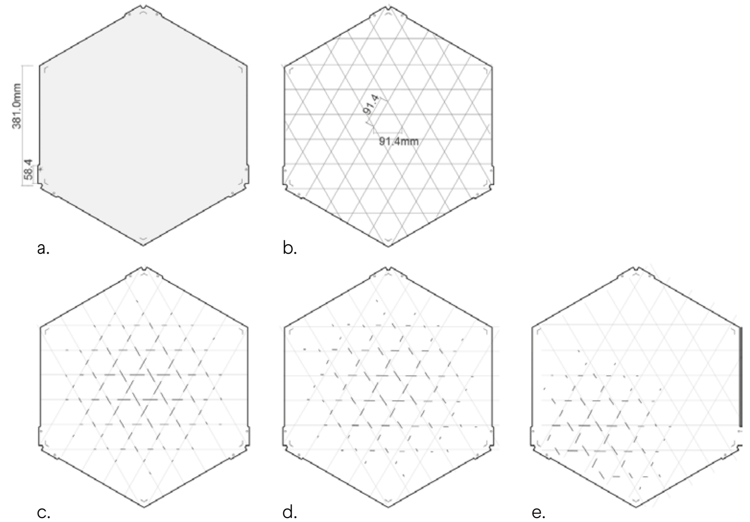
that absorb sound via a mechanism called Helmholtz resonance. This mechanism relies on defined air cavities with precision openings. Key to its effectiveness is a coordination between three geometric variables: the cavity volume, the aggregate size of cavity openings, and the thickness of the enclosure at the openings. These elements determine the frequency of resonance where absorption is most significant. Perhaps more importantly, the system of slumping, cavity definition, and perforations allows *Long Range* to begin as a flat surface and move gradually through diffusion and across a threshold into absorption. In other words, by invoking Helmholtz resonance, acoustic absorption is a natural outcome of an increasingly aggressive shaping process. Remarkably, since each panel starts off as flat, the slumped panels move through a continuous range of acoustic possibilities within the kiln along the path to their final form. Unlike additive and subtractive fabrication methods, in which a precise form is determined and obtained directly, the fabrication process of *Long Range* has all possibilities built in, and each panel is simply guided and halted at the desired place in its evolution.

It is possible to create openings that are too large or small, effectively pushing the primary frequencies outside the range of audibility or interest. The freedom of movement provided by the length of the cut lines within the auxetic patterns of *Long Range* gradually decreases as the pattern moves away from the centroid of its placement within the blank. The ability of the surface to unwind is reduced as the cut lines become shorter. Smaller openings are created, and this gradual restraint offers a chance to study shifts within the surface across different ranges of movement. Shifting within a singular pane can be further altered based on the placement of the pattern within the initial blank and in coordination between adjoining panes of glass. Within *Long Range*, the location of the patterns cut into the blanks was determined in relationship to neighbouring panes to focus on aggregate surface continuity. This allows for areas of concentrated opening or closure that are shared across multiple panes of glass.

The geometric characteristics that were modified across *Long Range* to tune acoustic performance are:

- volume of air contained between the pieces of glass
- quantity and locations of perforations
- sidedness of perforations or lack of perforations across the glass bubble (both, neither, or one pane perforated)
- concavity, convexity, or flatness of both sides or either side
- continuity of perforation pattern across neighbouring panes
- relationship of surface curvature to that of neighbouring panes

Integral to the understanding of tuning a material to acoustic performance, each pane of *Long Range* begins as the same flat pane blank and moves through a range of geometries and openings during the fabrication process (Fig. 10). As such, the relationship between the physical characteristics of the pane and its contribution to the acoustic spectrum – reflective, focusing, diffusive, absorptive – is achieved by deciding when in the process to stop the physical transformation of the glass. The sagging of the glass within the kiln correlates to the contained volume, the shaping of curvature and its concave or convex positionings, and the size of the openings. All of this is controlled by the kiln cycle, where time at sag temperature determines the final curvature and openings of each specified pane and pattern. This is further amplified by the decision to use auxetic patterning within the system. The auxetics allow for large openings while still maintaining the exact same starting surface area of material. The pattern is cut into the original blank as simple lines. The amount of material removed is limited to the width of the kerf of the jet stream. The auxetic pattern transforms these thin lines into wider openings as the surface twists or unwinds, substantially shifting the location of solid and void all within the same amount of material. This is counter to cutting a larger opening by way of a subtractive manoeuvre that would instead remove significant material quantities from the initial surface area.



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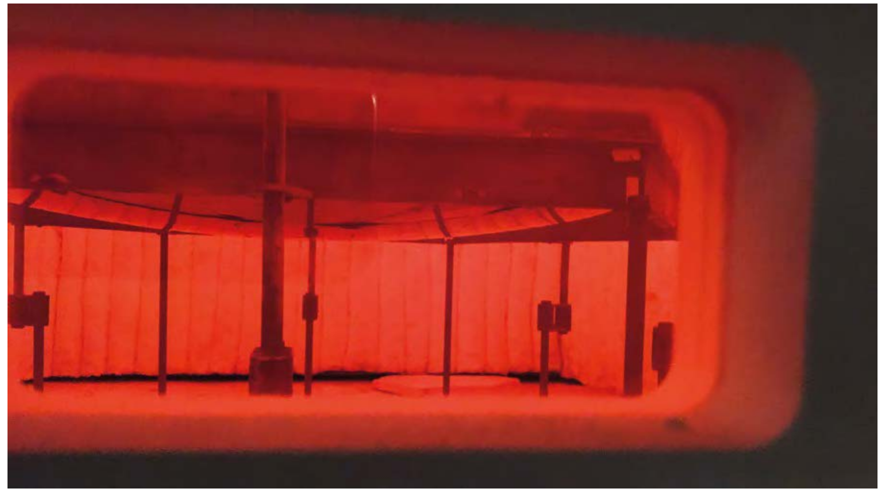

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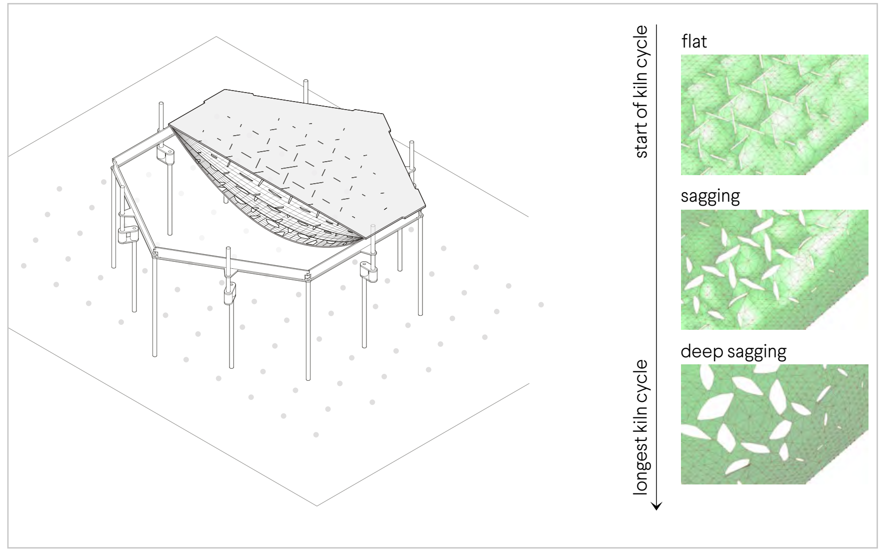

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6. The system utilises two sides to produce coordinated variation in surface behaviours as well as an enclosed internal volume accessible through openings. © Catie Newell, University of Michigan.

7. A series of glass bubbles are carefully coordinated across the entire length of *Long Range* to access a continuous gradient of acoustic behaviours. The flat end primarily exhibits acoustic reflection, the centre diffusion, and the severe end absorption and transmission, as seen from left to right in this photograph. © Zackery Belanger, Arcgeometer.

8. Each panel begins as the same hexagonal shape, an acoustically reflective blank, which is perforated with a modified regular hexagonal auxetic pattern. The quantity and location of perforations can be varied to produce different results in size, location, and extent of openings.

9. Kiln-formed catenary-sagging process with perimeter support ring. © Catie Newell, University of Michigan.

10. By starting with a flat pane in the kiln, a single panel moves through the spectrum of geometric possibilities in the fabrication process relative to curvature and openings. © Catie Newell, University of Michigan.

11. Location of perforations across the surface within an auxetic pattern determine points of inflection and opening across the surface. © Catie Newell, University of Michigan.

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Acoustic verification

Acoustic absorption was confirmed at Riverbank Acoustical Laboratories in Geneva, Illinois, US, following ASTM C423-17 – *Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method* (ASTM, 2017) (Fig. 12). This standard, which is comparable to its European counterpart ISO 354, yields test results from a reverberation chamber with and without the testing sample in place. Based on the difference between these two conditions, the acoustic absorption of the sample can be calculated. For *Long Range*, tests were conducted on three distinct regions of the surface, which were extracted for this purpose. A fourth, hypothetical region of *Long Range*, an area of all flat planes, was also tested (Fig. 13). Results indicate that absorption is present in all four samples and increases along its length as the shaping becomes more aggressive, as intended in the design (Fig. 14). Shaped glass panes are an unusual sight in laboratories that test for acoustic absorption, as the dominant assumption is that non-porous surfaces are useless in this regard. While the measured absorption was somewhat low in comparison with porous surfaces, it was significant, especially when considered in the context of the shaping of a room enclosure, as opposed to acoustic panel application. The acoustic testing of *Long Range* demonstrates a correlation between absorption, the severity of curvature, and perforation extent. Increasing surface area can yield greater influence on the dissipation of sound, indicating that traditional realms of acoustic behaviour may be part of a single continuum (Belanger, 2021).

One of the consequences of 20th-century acoustics is the prevalence of the idea that acoustic surfaces are not project-specific, that they can be added to any space that needs them. Their acoustic properties are seen as independent of the rooms in which they are applied, and they are objects that are separate from the uniqueness inherent to all spaces. This approach is more akin to choosing furniture than to designing a room, which may at least in part explain the common hesitation of architects to consider acoustics. *Long Range* is not a collection of acoustic panels designed to be applied onto substrates. It is a surface that intentionally avoids this categorisation by suggesting a modification of the enclosure itself, via a deep exploration of material and fabrication possibilities. Its acoustic properties are intrinsic, and are tuned as a system, with intentional relation to the aggregate system, during fabrication. *Long Range* demonstrates that additive acoustic treatments, with their implications for excess and energy, may be unnecessary to create visually stimulating and healthy acoustic environments.

Material performance

Given the combination of hardness and light transmission in conjunction with deformation made possible through thermal manipulation, glass is an exceptional material for investigating the relationship between the geometric composition of a surface or space and its acoustic properties. These ideas are not limited to glass, however. *Long Range* demonstrates that dominant opinions of the properties of a material may be unnecessarily confined by the limited formal deployment of that material in the past. It invites us to scrutinise other materials through similar exploratory processes, to potentially produce surfaces like *Long Range* with different materials. Each material will have different properties and ranges of possible scale based on inherent material behaviours, intrinsic material geometries and scales, applied material manipulations, and fabrication-specific detailing and form-finding. More widely, this approach invites material and fabrication choices that interlace with an intention to cultivate multiple performances within the same material application – be it acoustic, visual, thermal, or enclosure. A more closely curated material system offers opportunities for a reduction in material use, waste, or energy, while still achieving varied spatial performance criteria within one system. This would be a notable standard for a resource-challenged world. Though glass is not the only material that can be approached in this manner, there is an extraordinary potential to coordinate the surface and detail geometries of glass to the optical and acoustical performance of a space. When coordinated spatially, this offers architectural opportunities to realise a range of intrinsic acoustic and optic behaviours into an architectural system from its onset.

12. Conducting an absorption test across a portion of *Long Range* at the Riverbank Acoustical Laboratories, a National Voluntary Lab Accreditation Program, or NVLAP, for ASTM C423-17. © Catie Newell, University of Michigan.

13. Each circle indicates specific portions of *Long Range* that were tested at Riverbank Laboratories and showed varying degrees of absorption. Each coloured circle matches with notation in Fig. 14.

14. Chart showing readings for specific portions of *Long Range* in proceeding diagram. Absorption increases at nearly all frequencies from sample to sample moving along *Long Range*, as intended in the design, an important result in understanding changes along the surface.

15. The design and fabrication of *Long Range* was guided by acoustics, including wave-based simulation studies and the anticipation of Helmholtz resonance. Simulation still indicates wave dissipation along the spectrum at various times after start of sound. The aggregation was designed to have a gradient of rising acoustic dissipation from one end to the other.

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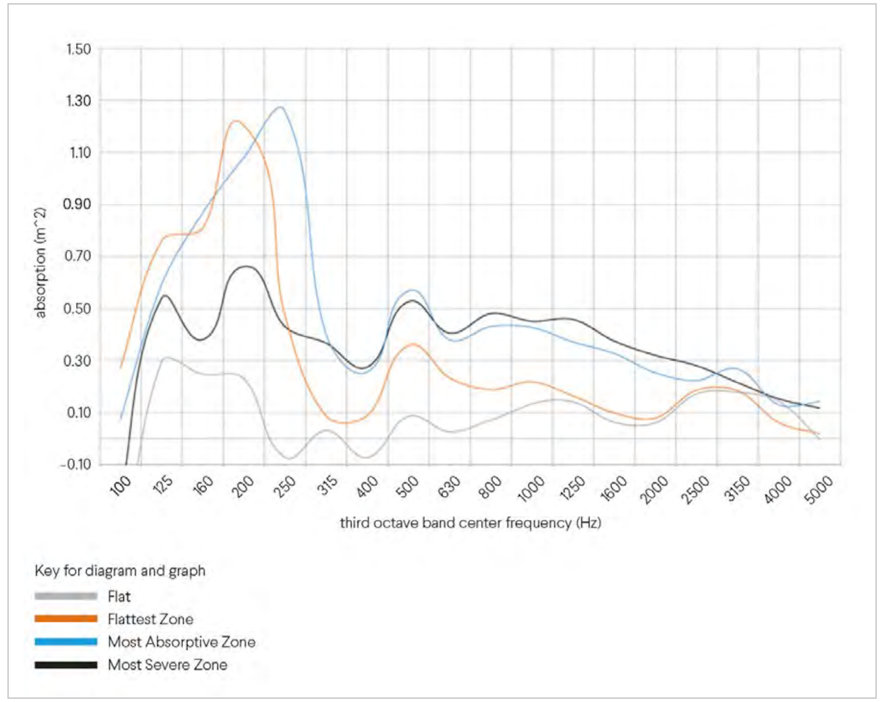

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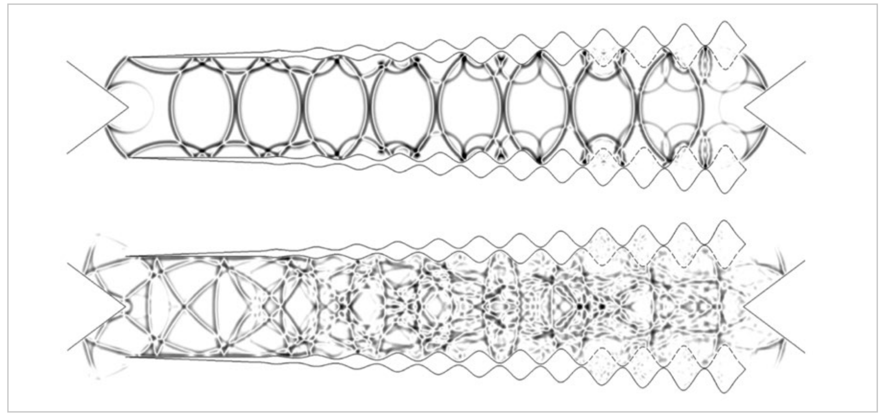

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LOCALISE
RECLAIM
INTEGRATE
RATIONALISE

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RECLAIM

CIRCULARITY AND REUSE

'ROOT' AND 'INNOVATION' THINKING AND DESIGN AT THE JINGDEZHEN IMPERIAL KILN MUSEUM

ZHU PEI
STUDIO ZHU PEI

The Imperial Kiln Museum is located adjacent to the Imperial Kiln ruins of the Ming and Qing dynasties, at the heart of the historical district of Jingdezhen, Jiangxi Province, China, on the east side of the Chang River. The museum is surrounded by buildings of different ages – from traditional residential dwellings and private kilns of the Ming and Qing dynasties to factories built after 1949, to commercial residential towers of the late 1990s – and the rich and diversified urban fabric has created a unique and profound historical and cultural context. The paper discusses how ancient local practices of vault construction and porcelain production, and the traditional use of recycled kiln bricks, have contributed to the thoughtful architectural language of the Jingdezhen Imperial Kiln Museum, expressive of the consanguinity between architecture, people, and porcelain.

The original architectural concept was developed along two main points: root and innovation. Root refers to the distinct natural, geographical, and climatic conditions of a region, as well as the survival mode and culture that bred from it. Innovation is an attempt to subvert the traditional concept of existing museums and create a new museum experience.

Site

Jingdezhen is known as a city that was '*born because of kilns, and flourished because of porcelain*'. People came from afar to settle down near the mountains and live close to rivers, dedicating their lives to building kilns and making porcelain. The trinity of porcelain kilns, workshops, and dwellings constituted the basic units of the city. Based on these, the prototype and structure of the city were established. Narrow lanes ran east to west, linking thousands of private kilns, to lead straight to the Chang River. In the hot summer, the narrow lanes extending under the eaves of the dwellings provided spaces that were fully shaded and sheltered from the sun and rain and formed wind tunnels for natural cool breezes. The old city's craftsmen would push their wheelbarrows along these lanes between the brick kilns and the Chang River to dispatch newly made porcelain and return with more clay and firewood. The main streets of the city have always been parallel with the Chang River, running from north to south, linking markets together to form a busy bazaar. Local residences are built to the Huizhou typology, with vertical courtyards, enclosed pitched roofs to gather water, and long eaves extending out of the façade. In summer, the eaves provide shade and create a chimney

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effect, which guarantees good natural ventilation. The urban layout and architectural style not only reflect the local lifestyle, but also display the local long-standing wisdom of the people in dealing with the hot and humid climate.

A wind device

With hot and rainy summers being a significant climatic condition in Jingdezhen, one of the most important ideas behind the design was to create a porous, sponge-like building that maximises natural ventilation, while extending shelter from the sun and rain without the need for air conditioning during summer. Both ends of the long axis of each vault of the museum complex are open. These open, semi-outdoor vaults, and closed indoor vaults, are staggered with each other, alternating between the solid and the void, shaping the porous characteristics of the museum analogous to a 'sponge architecture'. The long axis of the vault is arranged along the north–south direction. The vault not only blocks the sunlight on the west side, but also provides sun shading and shelter from the rain in a design that turns each vault into a wind tunnel allowing cool breezes to pass through, and oriented especially to capture the dominant north–south wind direction during summer. In the five sunken courtyards of varying sizes and scales, bamboo has been planted to create a poetic space, where the underground level is illuminated by natural light. This presents a typical Jiangxi Province feature and creates the chimney effect experienced in local vertical courtyards, which helps to enhance natural ventilation. On a hot summer day, when visitors step into the museum, they will always feel a cool breeze. The whole building resembles an installation composed of wind, air, and shadow, intelligently blending and coexisting with nature.

1. Views of the amphitheatre, ruins, and open vaulted area. © Schranimage.

2. Site view showing the urban context of the Jingdezhen Imperial Kiln Museum. © Studio Zhu Pei.

The most successful feature of the Imperial Kiln Museum is that it does not need to use air conditioning in summer.

Incomplete integrity

The Imperial Kiln Museum is composed of more than a dozen brick vaults of various volumes arranged in a north–south direction. They are a whole but separated from each other; integrated with the complexity of the context and in the appropriate scale, yet held with a humble restraint. On the one hand, the scale of the vault structures is close to that of the surrounding traditional brick kilns, carving a smooth transition between the surrounding large-scale factories, residential buildings, and traditional houses. On the other hand, the uneven length, irregular shifting, and incomplete architectural profile of the vaults skillfully compose an organic stitching with the surrounding uneven boundary. The strategy of 'incomplete integrity' has often proven to be forward-looking in dealing with the ever-changing, and unpredictable, regeneration of historical districts. During the construction of the museum, new archaeological sites in the area were discovered and excavated. While the integration of the site with the museum building strengthens the archaeological and anthropological characteristics of the museum, it also proves that the strategy of small-scale volumes and incomplete integrity can be applied flexibly in the nuanced environment of the historical district. Through the spatial coordination of the vaults, the newly discovered ruins were woven into the internal space of the museum.

Prototype and construction

The structural form of the Imperial Kiln Museum building draws inspiration from the old traditional local brick kilns of Jingdezhen. Different from the Roman arch, a traditional brick kiln is not a simple geometric shape but is made of a set of complex double-curved surfaces, which conveys the typical characteristics of the oriental vault. When constructing a traditional brick kiln, kiln craftspeople did not use scaffolding; rather, the building was completed with the assistance of gravity, by taking advantage of the dislocation of the bricks. If you were to carefully observe and study the construction process of the double-curved vault (*luanyao*), you would be surprised to find that olden-day craftspeople ingeniously broke down the extremely complex double-curved vault that resembles the shape of an eggshell into countless single-curved surfaces, by making countless horizontal cuttings along the long axis, in which the thickness of the cuts is the exact thickness of the kiln brick itself. These

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3. Restoration of a traditional brick kiln. © Studio Zhu Pei.

4. Reclaimed kiln bricks. © Studio Zhu Pei.

5. A specialised, adjustable, and movable scaffolding system. © Studio Zhu Pei.

craftspeople used their fingers to control the dislocation of every single-curved surface to complete the construction of the entire double-curved vault. This method, though ancient, is the same process used today to generate double-curved forms using the computer.

A variable and movable scaffolding system was developed for the construction of complex double-curved vaults with an inner and outer layer of bricks and a concrete middle, resembling a sandwich section. The ends of the scaffolding are telescopically adjustable metal poles, which bear against the wooden keels and flexible wooden formwork. Tracks are laid on the lower part of the scaffolding system. During construction, the movable scaffolding system moves forward step by step along the central axis of the vault. The cross-sectional shape of the vault is adjusted little by little, and the curvature of it changes accordingly. This simple and adjustable scaffolding system was used to build complex double-curved vaults.

Material

In Jingdezhen, the practice of reusing kiln bricks has lasted for a thousand years. When a traditional brick kiln has worked for a year at the most, the kiln bricks have completed their life cycle, taking on decaying heat storage properties. Hence, they would be replaced by new bricks. The old bricks with their 'kiln sweat' (a crystalline compound of wood ash and clay minerals vaporised through years of ceramic firing) are mixed with new bricks to become the primary construction material to build local residential houses. This tradition continues to this day. The practice of mixing old and new bricks has been inherited by the Imperial Kiln Museum; sometimes, the new bricks are mixed with sand from crushed saggars (refractory-baked clay boxes used to hold finer ceramics during firing).

The museum buildings are inextricably enmeshed with the history of the site, having been finished inside and out with an unending supply of used bricks, which have accrued over time from the relentless, cyclical demolition and reconstruction of kilns in order to maintain the high temperatures required to fire porcelain. These narrow, slightly polychromatic, unevenly burnt bricks are judiciously mixed with new bricks of the same character and proportion. These bricks, when laid carefully together, serve as the permanent formwork of the reinforced concrete shell vaults, both within and without.

Space experience

The exhibition halls of the museum are located at ground level and underground, with the foyer located on the ground level. This arrangement allows visitors to approach the building with a sense of affinity and to be impressed by its scale, which is close to that of the existing buildings in the city. More importantly,

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the spatial experience that visitors entering the building encounter is akin to that experienced by the craftspeople who entered the brick kilns in the past.

As visitors wander through the Imperial Kiln Factory Heritage Park, moving between scattered bamboo groves and pebbled sections, crunching gravel under their shoes, they view in the distance a group of long, gently lying, low brick vaults resting serenely beside the hills and surrounded by historical houses, factories, and residential buildings on three sides. The long pond between the Imperial Kiln ruins and the Imperial Kiln Museum gently guides the circulation. Groups of flattened lake stones lie docile under the water, sometimes peeking out, like schools of fish swimming in the water, their backs occasionally breaking the cover of the surface. While strolling, visitors are treated to the sound of the flowing water in the pool, accompanied by the rustling of bamboo leaves in the breeze and the chirping of birds in the trees; as if they are in a familiar bamboo forest, surrounded by streams and hills – a natural landscape typical of Jingdezhen.

Crossing the calm water via the bridge, one enters the long, vaulted foyer, which is wide and high in the middle, and gradually tightening at the sides – with wood-framed glass windows and doors at each end. The bricks are arranged vertically to create double-curved surfaces, and the tops of the vaults are pierced with many small circular skylights, like the wood-throwing/observational holes in a traditional brick kiln.

From the foyer, moving to the right through several brick vaults, past the bookstore and café, visitors finally reach the tearoom, which is the semi-exterior space of the vault structure; here, the shimmering waters of the pond under the sunlight reflect wavy ripples gliding in iridescent stripes across the rough surface of the brick. The low, horizontal opening here curiously suggests that visitors should sit on the ground; on doing so, they receive an unexpected surprise: the long, horizontal ground surface of the Imperial Kiln Museum archaeological site is led into view when one is at eye level with the opening. This is different from the spatial experience of viewing the Longzhu Pavilion in the Imperial Kiln ruins through the vertical slits in the wall prior to entering the hallway, yet the feeling of surprise is similar.

From the foyer, moving left, at the end of the double-height exhibition hall, visitors can either look down at the underground galleries, rest their eyes on the sunken courtyard planted with bamboo and enclosed by the restoration studio behind the transparent glass wall, or take in the view of the residential cityscape that forms the backdrop of the museum. To the left of the end, visitors can cross the vault to the vestibule of the auditorium shaped by brick vaults and fair-faced concrete walls; to the right of the end, huge vaults 'cracked' by occasional slits of natural light invite them to cross through to the semi-outdoor vaulted space, where the archaeological site – located 2m below ground level – is sandwiched between two open vaults at the north and south, with the outdoor amphitheatre under the northern vault and the semi-outdoor exhibition hall under the southern one. From here, visitors can look over to the archaeological site and the sunken courtyard and cityscape in the distance or descend to the site and rest on the steps of the amphitheatre to soak in the ambiance. They are then led to another smaller vaulted indoor gallery for a walk-through, where the 'route' ends with a gentle fair-faced concrete staircase, which takes them down to the underground space.

Five sunken bamboo courtyards of varying sizes and shapes are scattered along the main exhibition circulation at the end of each gallery, not only allowing natural light and ventilation within the underground space, but, more importantly, also presenting the opportunity for visitors to step into a courtyard at any time, as they walk into different rooms, to take breaks, pause, and even observe museum staff restoring historical porcelain in the restoration room. Eventually, visitors are led to the stairs in the gap between the two vaults, where they can reach out and touch reused kiln bricks burnished with kiln sweat, to then be guided by the natural light filtering in back to the starting point, with the foyer on the left and the auditorium on the right.

6. The masonry of new and old kiln bricks. © Studio Zhu Pei.

7. Construction detail of arch opening between two vaults. © Studio Zhu Pei.

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8. Aerial view of the Jingdezhen Imperial Kiln Museum showing the spatial coordination of the vaults. © Tian Fangfang.

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9. View of the auditorium and sunken courtyard. © Studio Zhu Pei.

The auditorium is under a standalone vault with a high dome and has steep seating and a podium at the end. When the celebrated Japanese architect Arata Isozaki visited the Imperial Kiln Museum, he called it a 'spiritual space' akin to a church; it is no longer a black box that shuts out all distractions on the outside. A narrow horizontal slit has been cut along the western side of the vault and flushed with the water surface so visitors in the vault can view a reflection of the Imperial Kiln Factory site (that sits on the western side) captured against a background of lake stones in the water. The thick concrete crossbeam at the upper part of the horizontal slit joint supports the brick vault – reflecting the characteristics of tectonic forces. A narrow vertical slit has been cut into the end of the north side wall, capturing the sky, the urban landscape, and the sunken courtyard. As a result, people can feel the slightest change in the elements outside, at any time, even though they are sitting in the auditorium.

The permanent exhibition circulation is completed by a closed horizontal up-and-down loop. The temporary exhibition circulation can be incorporated into this loop, or follow a separate route, as it has its own separate entrance and exit. Another feature of the museum is the integration of the porcelain restoration process as part of the exhibits. The office entrance is located at the north end of a separate vault at the southeastern part of the building group, as it is tranquil and secluded here. Lorries can back into the vault via a loading area at the south end, which is enclosed and safe for loading and unloading.

In a nutshell, then, the Imperial Kiln Museum, invites visitors to walk through a series of grey spaces shaped by architecture and nature. The vault structure, together with five sunken courtyards, creates a porous architecture with void and solid interlocked, and interior and exterior intertwined. Inside the museum, visitors find themselves captured by a feeling that is both familiar and alien. The rich lighting effects presented by the natural light that is guided in leads them to meander around the space, piquing their curiosity to explore, moving them from one space to another. This creates a museum journey that reconciles the kiln, the porcelain, and the people.

The consanguinity between architecture, people, and porcelain

Brick kilns not only form the origin of the city of Jingdezhen, but also the living and public spaces of local people. They preserve the warm memory that is inseparable from life in the city in the old days – during harsh winter days, children would pick up a hot brick from a kiln on their way to school, and place it in their schoolbags to keep themselves warm throughout the day. In winter, schools were often moved close to the warm porcelain kilns; in summer, when the brick kilns were not used, they provided humid, cool air naturally, and became gathering places for children, young people, and the elderly, to interact, play, and pass time. The broken walls of these kiln ruins, which have passed down immortal memories from generation to generation, are the source of creative inspiration for the Imperial Kiln Museum. The unique oriental vault as the prototype of the porcelain kiln, as well as the lasting memory of the kiln bricks, has shaped the consanguinity of the kiln, the porcelain, and the people. The brick kiln has long been a vital part of cultural memory and urban life in Jingdezhen, and it has unsurprisingly become the structural form of the Imperial Kiln Museum.

Today, when people visit, they are reminded of the scene of local people working in the porcelain kilns. This experience has reshaped the consanguinity between the kiln, people, and porcelain.

The 'rootedness' not only involves exploring and engaging with the 'past' nature of past things, but, more importantly, it involves comprehending the present nature of past things. If an architectural work does not have the 'rootedness' of historical consciousness, it is equivalent to having no fulcrum in the vast universe, and is unable to enquire into the existing architectural ideological system, and unable to be 'creative'.

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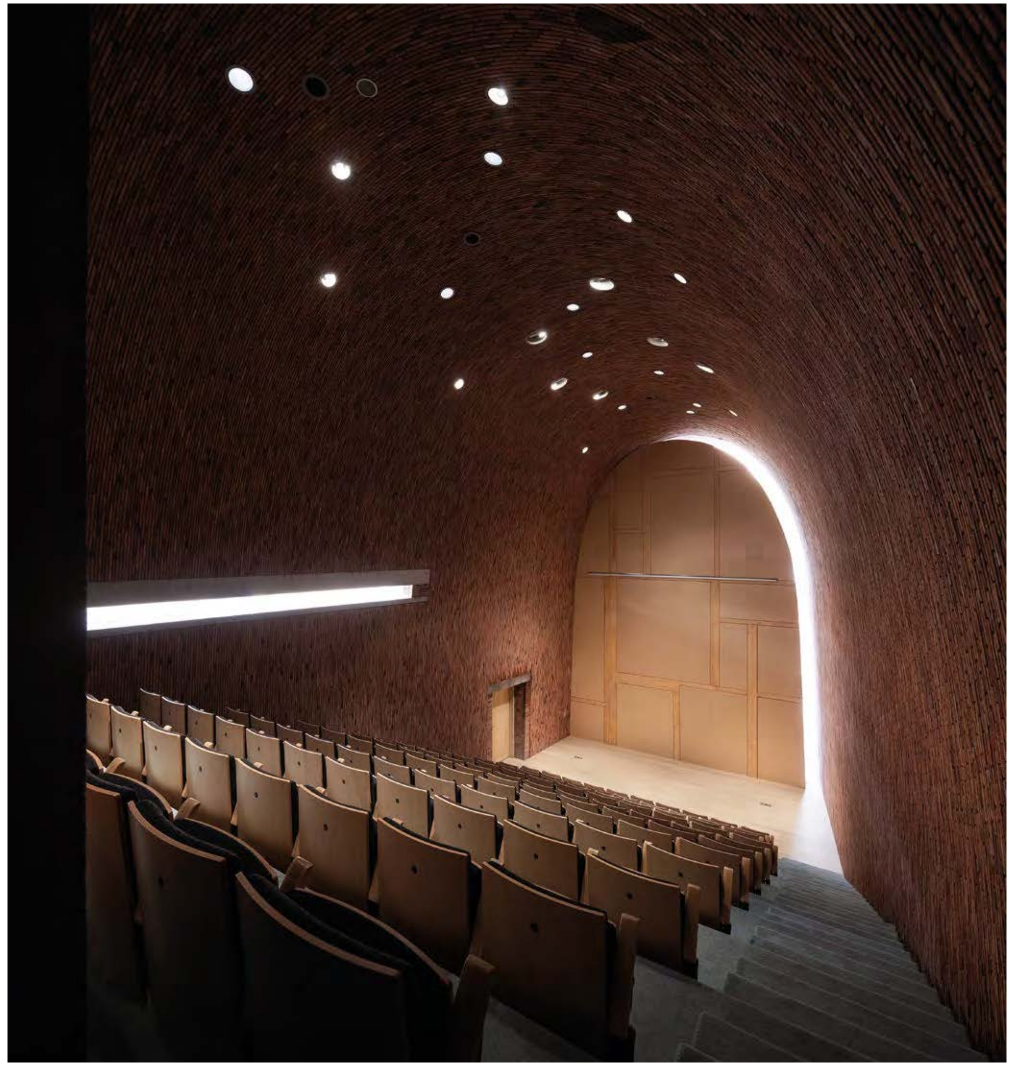

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10. The vaulted foyer of the Jingdezhen Imperial Kiln Museum. © Schranimage.

11. View towards the open vaults. © Schranimage.

12. The exhibition spaces at ground and underground levels. © Schranimage.

13. The auditorium features a standalone vault with a high dome and steep seating. © Schranimage.

14. Detail of vault showing the play of light on recycled kiln brickwork. © Schranimage.

STRIATUS 2.0
PHOENIX – IMPROVING CIRCULARITY OF 3D-CONCRETE-PRINTED UNREINFORCED MASONRY STRUCTURES

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BÜRGIN CREATIONS

Introduction

This paper describes the realisation of Striatus 2.0: Phoenix, a permanent, 3D-concrete-printed, dry-assembled, unreinforced-masonry arched footbridge composed of dry-assembled, 3D-concrete-printed blocks (Fig. 1). The research presented in this paper details the improvements that were made to the novel integrated design, engineering, and fabrication framework and to the manufacturing and assembly processes used in the realisation of Striatus (Bhooshan *et al.*, 2022a, b; Dell'Endice *et al.*, 2023). This paper builds on the relevance of the computational masonry paradigm to deliver the ecological promises of 3D concrete printing (3DCP) and provides a detailed comparison between the two iterations of the bridge (Figs. 2, 3).

State of the art

Relevant precedent 3DCP structures are: the very first 3DCP pedestrian bridge installed at the Institute for Advanced Architecture of Catalonia (IAAC), Barcelona (IAAC, 2016; IAAC, Acciona, 2017; Wangler *et al.*, 2019), bicycle bridges in Gemert (Salet *et al.*, 2018) and Nijmegen, both in the Netherlands (van der Kley *et al.*, 2018), and a pedestrian bridge in Shanghai, China (Xu *et al.*, 2020). It can be noted that none of them use the unreinforced-masonry (URM) paradigm (Bhooshan *et al.*, 2023). The URM design and construction techniques are perfectly compatible with the compression-dominant, orthotropic material properties of layered 3D-printed concrete. For an in-depth review, we refer the reader to Bhooshan (2023) and Dell'Endice *et al.* (2023).

Rapid urbanisation and climate change heightens the urgency of addressing the circularity of building construction (Wangler *et al.*, 2019; Block *et al.*, 2020; Fivet and Brütting, 2020). In this context, the widespread and relatively cheap availability of concrete, the low cost of the technological requirements for its use, and its beneficial material properties make it an important material. However, given the expected high-volume use of concrete in the immediate future, it is vital to mitigate the associated carbon emissions (Monteiro *et al.*, 2017). Decarbonisation of the concrete industry is critically important.

The Striatus bridge

The Striatus bridge (2021) was designed to be installed, dismantled, reassembled, and repurposed, demonstrating how the four Rs of circularity (reduce, reuse, repair,

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recycle) can be applied to concrete structures. See Bhooshan *et al.* (2022a, b), and Dell'Endice *et al.* (2023). The following lessons were learned:

1. The size of the 3DCP blocks challenged transportation and manoeuvrability during the assembly. Improved alignment strategies are needed.
2. The assembly strategy adopted, from the supports towards the centre, lacked a strategic approach to close the resulting gaps when placing the keystones.
3. The assembly relied entirely on the precision of the falsework. Some errors in its design led to imprecisions. Additionally, an improved strategy to reduce single-use materials for the centring and increase reusable parts is needed.
4. The 3DCP process involved inherent tolerances that were not quantified. As a result, the real block length was not cross-referenced with its digital counterpart, introducing an additional layer of uncertainty that, in turn, impacted the accuracy of the assembly.
5. The 3DCP blocks were fabricated using high-strength (90MPa) concrete with aggregates measuring less than 1mm. Transitioning to larger aggregates would reduce the percentage of cement in the mix, while using lower-strength concrete would enhance the use of recycled raw materials in the cement recipe.

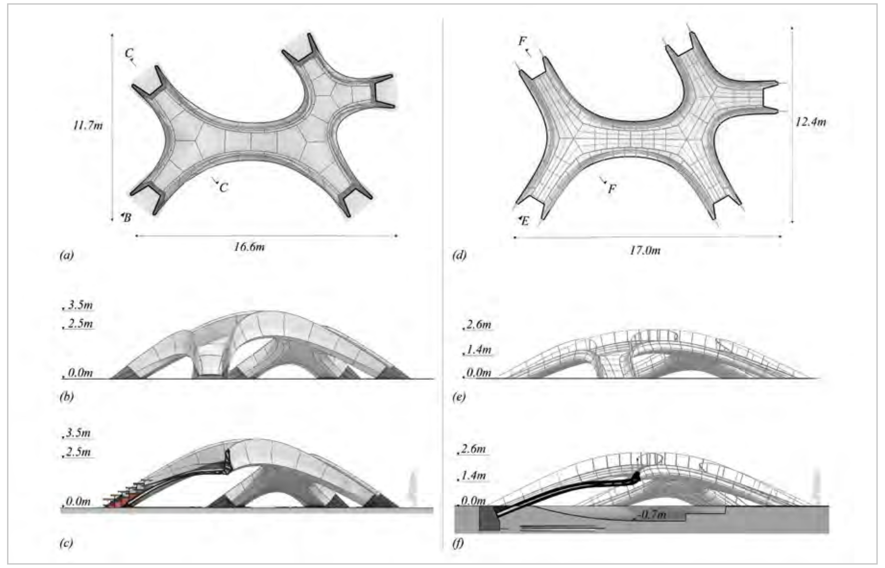
The transition from Striatus to Phoenix considered all these issues and challenges. It aimed at enhancing the structure's sustainability by focusing on three objectives: (i) optimising the carbon footprint, (ii) reducing the reliance on virgin resources through improved circularity, and (iii) extending the structure's design life.

Striatus 2.0: Phoenix bridge

Phoenix, being the second iteration of Striatus, builds on the collaborative, multi-author design-to-production (DTP) toolchain described in Bhooshan *et al.* (2022a), and Dell'Endice *et al.* (2023), with the improvements in each thread detailed below.

Architectural and structural design

The geometry of Phoenix is shallower than that of Striatus (Fig. 2). It is better suited for a pedestrian footbridge and does not require steps. The number of blocks has been increased to improve manoeuvrability and adjustment and reduce transportation requirements (Fig. 4), leading to a new assembly system detailed in Assembly strategy. Reducing the dimensions and weight of the blocks promoted their compressive-only behaviour, discouraging bending stresses (Ranaudo *et al.*, 2022). The reduction in the height of the balustrade blocks gave Phoenix a lighter



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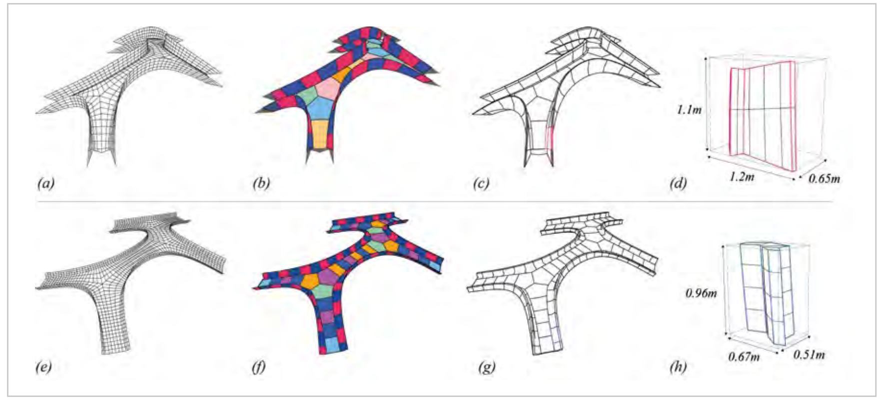

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1. Completed Phoenix bridge at the Holcim Innovation Center, Lyon, France. © Alessandro Dell'Endice.

2. Schematic drawings showing the shallower arch design and less deep balustrade blocks of the Phoenix (right) versus the Striatus (left) bridge.

3. The Striatus bridge exhibited at the Giardini della Marinaressa, Venice, Italy, in 2021. © Naaro.

4. Striatus (top) versus Phoenix (bottom): (a–c) versus (e–g) compare the block subdivision; (d) and (h) compare a typical balustrade block.

5. Detail of the handrail installed on a T-shaped steel element inserted between neoprene pads at the interface. © Cecilia Vuillermoz.

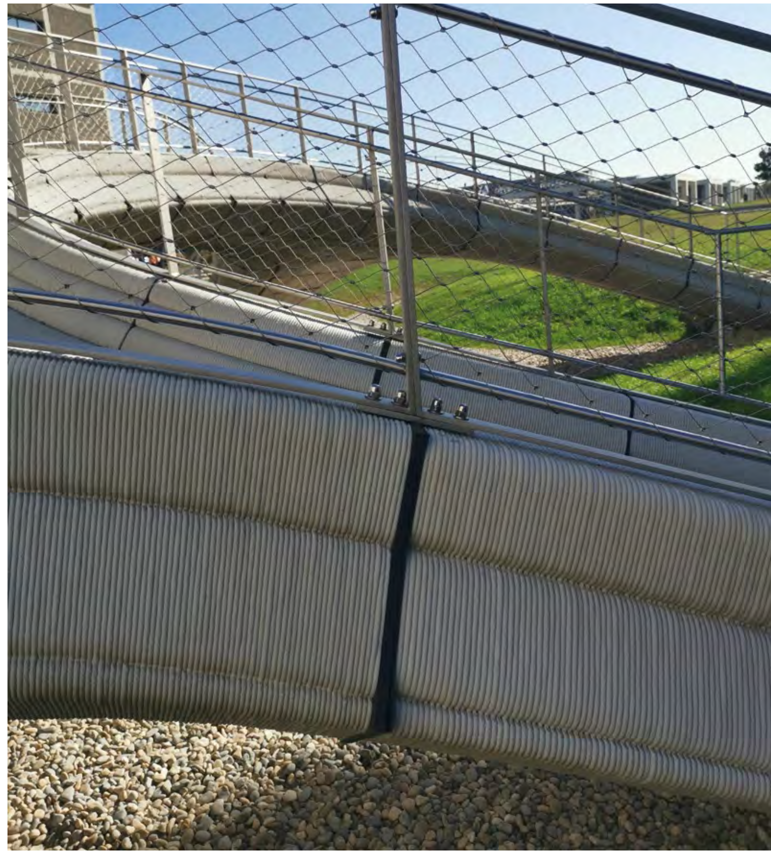
appearance compared with Striatus and required the development of a handrail system, clamped between the blocks, taking advantage of the thrust of the arch (Fig. 5). The structural design also involved the internal stiffening schemes of the blocks, as described in Print-path synthesis. Since the deck blocks only require curvature in the spanning direction along the bridge's skeleton and laterally receive compression forces from the balustrade arches, the cross-section in the short direction does not need curvature. In other words, there is no arch action in the short direction of the bridge. Consequently, the internal stiffening scheme, to reduce the free span of the deck blocks' horizontal top and bottom layers, was simplified and reduced to vertical stiffeners only. With the intention of designing a permanent structure, a few expedients were adopted to improve the robustness of the system:

1. The structural depth of the deck blocks was increased, which enlarges the equilibrium solution space for live load cases.
2. The cross-section at the base of the balustrade blocks was increased.
3. In the cross-section of the 3DCP components, the printed layers were thicker (nominal thickness 48mm), avoiding double layers with potentially imperfect bonding.
4. The shallow geometry reduced the curvature variation in each 3D-printed block, namely the angle between the start and end printing planes, making the layer height variation in a single component less extreme.

The structural design of Phoenix closely followed Striatus, comprising three phases. First, form-finding was conducted using thrust network analysis (TNA) (Block, 2009). Subsequently, materialisation, discretisation, global equilibrium, and displacement capacity were accomplished using the Discrete Element Modelling (DEM) method, through *compas_3dec*, which uses the software 3DEC by Itasca as a solver in the background (Dell'Endice, 2023). Lastly, local stress assessments were carried out using finite element modelling (FEM) analysis.

Structural analysis

For Phoenix, SLS and ULS load combinations, differential settlements, thermal loads, creep analysis, snow, wind, and horizontal loads according to the Eurocode were applied using the FEM software ABAQUS. The FEM analysis was conducted on the discretised model, allowing the formation of hinges/openings at the joints. The average compressive stress experienced with SLS simulations was only 2.65MPa, with a peak of 5.2MPa



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in just one loading case. For ULS, the average calculated compressive stresses were 5MPa, with a peak of 9.3MPa in only one loading configuration. These results confirmed that compression stresses are not an issue, being a mere one-tenth of the nominal compressive capacity of the 2K ink employed (50MPa) and one-fifth of its design strength after considering safety factors. As expected, the funicular geometry and informed discretisation, i.e., stereotomy, of the structure play a significant role in maintaining remarkably low compressive stress levels within the structure.

The design of the individual 3D-printed components also paid attention to the tensile strength of the printed material. The 2K ink used for Phoenix has a nominal tensile strength of only 2.85MPa and a design tensile strength equivalent to 2.28MPa (for SLS) and 1.52MPa (for ULS). The FEM analysis has shown that, for SLS loading conditions, the structure experiences average tensile stresses equal to 1MPa and, only in one case, 1.8MPa. For ULS configurations, the structure experiences, on average, 1.39MPa with peaks of 1.5MPa, remarkably close to the ULS tensile strength equal to 1.52MPa.

Print-path synthesis
The cross-section of the deck blocks was updated from a triangular bracing to vertical stiffeners. The dual-layer print path used in Striatus was also updated to a single-layer print path with double the print width (48mm), which halved the overall print length (29km). The so-called signed distance fields (SDFs), used to generate the print paths, were updated accordingly. For both the deck and balustrade blocks, the initial procedure to compute the base profile from the interpolated print planes remains the same. The resultant SDF (f_{result}) constitutes the Boolean of four individual SDFs, each serving a specific purpose:

- base profile polygon f_0
- offset polygon $f_1 = f_0 + 0.5 * \textit{print width}$; f_1 controls the cross-sectional print thickness based on specified print width and f_0
- brace f_2 = *line SDF at brace points;* f_2 provides local stiffeners in each cross-section
- trim f_3 = *perpendicular line SDF of brace;* f_3 aids in the creation of one continuous print profile
- resultant $f_{result} = (f_1 - f_2) \cup (f_3)$

Typical bottlenecks in the computational time of SDFs (Erleben and Dohlmann, 2008) were alleviated by using GPU-based parallel computing. It accelerated the computational production time and increased the field resolution for greater control of output contours and faster generation of the print paths for all the blocks: 112 minutes for Striatus (53 blocks, single thread CPU) versus 1.8 minutes for Phoenix (104 blocks, GPU).

The feature-based sampling procedure described in Bhooshan *et al.* (2022b) was used in the post-processing stage to create one contiguous print path from the SDF contours, which have uneven sampling. The maximum sampling distance in Phoenix was increased from 10mm to 15mm to reduce the total number of points supplied to the robot, while still having minimal deviation from the block geometry. Varying print widths were used based on the outer and inner segments created by the feature points.

Material development
To address the material's sustainability targets, a custom-made, proprietary TectorPrint ink was developed for the project. As explained in Architectural and structural design, the design improvements relaxed the requirements on the layer thickness and width. In general, the narrower the layers, the higher the required material strength and consequently the material CO2eq footprint, as the water-to-binder ratio and the admissible maximum particle size are reduced. While Striatus was based on a 90MPa micro mortar with 1mm maximum size sand, in Phoenix, because of the 24mm print width, the layer width was increased to 48mm such that a 50 MPa mortar with 2mm maximum size sand could be used. The circularity of the mix was improved by using a fully recycled cement, type CEM III/A 42.5 N, with clinker made entirely of recycled minerals (Holcim lance le premier clinker 100% recyclé au monde, 2022) in combination with slag, and demolition sand from Striatus included in the dry mortar fraction.

Altogether, this resulted in a third of the ink coming from recycled materials. Furthermore, the CO2eq footprint of the ink was optimised by increasing the proportion of local material through the use of local sand (sourced 15km from the printing facility), which meant that half of the ink was made up of local materials. The local sand was mixed with the reduced dry mortar fraction in the printing facility when preparing the successive batches of ink, to feed the robot.

A 2K technology was used to ensure optimum processability, so that:

- The material is still fluid at the end of the batch mixing, with ad-hoc slump retention during the duration of batch consumption for printing.
- Buildability of the structure is tuned on demand, depending on printing speed requirements, by a secondary admixture (optimised in this project for the selected binder) introduced in the printhead where it is mixed just prior to printing with the fluid material fed from the batch mixer.

Outside building codes, 3D printing brings certain challenges (potential weakness of interfaces between layers, risk in curing due to the absence of formworks, so that drying starts from material deposition). As a result, the in-situ performance of the ink was checked both on samples cut from prints and on structural elements. Each structural test was run twice, with good consistency of results and sizeable safety margins.

Fabrication
By reducing the block size, the printing process benefited from removing the raft prints, necessary in Striatus due to larger blocks with higher curvature (Bhooshan *et al.*, 2022b). Another pertinent change was the thicker monolithic external layer, while the internal bracings were established with thinner parallel/double layers.

While the print paths for the Striatus blocks were designed in parallel layers, for Phoenix, monolithic outer layers of 48mm thickness were applied. Compared with Striatus, the GCode definition was expanded to include layer-width parameters per target in order to align robotic speed and the required material volume per target. To establish a continuous path, the internal bracings were established as parallel layers at half the width of the outer layers, which allowed Phoenix to place material as required (Fig. 6). The omission of raft layers enabled the blocks to be packed for transport immediately after curing, eliminating the additional step of raft removal.

Overall, the print time for all blocks was 67 hours, compared with 84 hours for Striatus, while the weight of both bridges is similar (around 25t). Next to time savings due to the avoidance of raft prints, a higher rate of mortar flow in the extrusion process of 3.2l/min accelerated production.

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6. 3D printing of a block with a monolithic external layer. © incremental3D.

7. Crane lifting of the cassette falsework system with blocks preassembled. © Cecilia Vuillermoz.

8. Placement of one cassette on the scaffolding system. © Cecilia Vuillermoz.

9. Dismantling the scaffolding and falsework system after decentring. © Alessandro Dell'Endice.

Assembly strategy
The falsework and assembly logic of Striatus were entirely reworked. The new objective was to enhance assembly precision while minimising single-use falsework components. The bridge was dry assembled with neoprene pads inserted at each block interface to avoid stress concentrations or assembly misalignments. The base of the falsework system consisted of standard scaffolding towers positioned along the central axis of the bridge, while the waffle system was divided into separated components called cassettes (Fig. 8).

To reduce the number of custom, single-use components, the depth of the waffle and the number of elements were minimised, while standard steel beams were introduced as part of the waffle's structure, reducing the volume per m^2 of timber by 50%. By working per cassette, the lighter

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blocks could be precisely arranged with the neoprene pads in between. Thereafter, the cassettes were lifted onto the scaffolding towers and registered in the right place following predefined measurements (Fig. 7).

Assembly followed a predefined sequence, starting from the centre and working towards the supports, where a gap of 2.5cm was left from the foundations (Fig. 8). This strategy was adopted to control the fabrication tolerances and assembly imprecisions in the sensitive middle, and to lump them at the last interface with the supports, where they could be compensated by filling the resulting gap with mortar, after the assembly and before the decentring. After the decentring, the structure successfully underwent a structural test, where four different loading cases were simulated by adding sandbags to the deck area.

Circularity and sustainability

3D-printing ink
From Striatus to Phoenix, the ink was optimised from a C90/105 to a C50/60 mortar, using a local and coarser sand, mixed with a dry mortar premix (the latter including demolition sand) in the printing factory. As a result, the amount of recycled material in the ink reached one-third of the weight.

Altogether, a footprint reduction of 40% CO2eq per m^3 of the 3DCP ink was achieved, mostly stemming from the decline in the strength category of the material. In detail, reducing the nominal compressive strength from 90MPa to 50MPa had an impact of one-third on the global CO2eq savings, using coarser and local sand one-quarter, using a low-carbon cement two-fifths; the route optimisation had an impact of one-sixth as well.

Comparison of the two footbridges
Both versions were compared in terms of carbon footprint. Rescaling accounted for difference in span (14m for Striatus, 16m for Phoenix) and deck surface (43m^2 for Striatus, 53m^2 for Phoenix). The latter was chosen as the functional unit, and therefore Striatus was rescaled to a 53m^2 deck surface area. Excluding the foundations, which are in both cases not representative and/or optimised solutions, the results show a 25% reduction of the carbon footprint, with the following key evolutions of the footprints:

- 34% reduction for the {deck + balustrade}
- 60% increase for the elastomer joints
- 62% reduction for the formwork
- 100% reduction of the cover footprint

However, a diminished CO2eq footprint is just one aspect of the overall picture. As mentioned in the introduction, this bridge is designed as a permanent structure and engineered for circularity, a factor not considered in the carbon calculations.

Future research
Future research in the domain of 3DCP and URM structures offers a wide range of avenues for exploration and improvement, including:

1. Enhancing material performance in tension
2. Rethinking interfaces
3. Innovating the activation mechanism
4. Integrating circularity in carbon footprint assessment
5. Refining measurement and reference systems

10. Completed 3DCP block assembly in preparation for handrail installation. © Cecilia Vuillermoz.

11. Intrados close-up of the completed Phoenix bridge at the Holcim Innovation Centre, Lyon, France. © Alessandro Dell'Endice.

Conclusion

The Phoenix bridge represents a significant research advancement in URM structural logic applied to 3DCP, addressing critical challenges encountered in Striatus, focusing on circular construction, environmental impact reduction, and structural robustness.

Advancements include: the sustainability of the concrete ink which incorporates recycled aggregates from the disassembled Striatus blocks, overall structural performance, optimising the print-path synthesis and 3D-printing process, minimising material waste, and devising an assembly strategy that maximises standardised off-the-shelf components, reducing the need for custom-made, single-use parts.

The Phoenix bridge project represents a significant advancement in applying 3DCP and URM principles for sustainable construction. It offers valuable insights into circular construction practices and environmental impact reduction while pushing the boundaries of this innovative technology.

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MARINA SPA PROTOTYPE
SMALL-SCALE AGILITY AND TIMBER WASTE STREAMS FOR COMPLEX TIMBER STRUCTURES

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Introduction

This paper presents a project designed and constructed for the exhibition *Women in Architecture* at the Danish Architecture Center (DAC) in Copenhagen in the spring of 2022. The project was developed by a geographically dispersed and multi-disciplinary team of architects, researchers, consultants, and fabricators. An entirely digital delivery approach necessitated a tight collaboration and fast feedback between all team members. Furthermore, non-standard material resources – reclaimed timber flooring off-cuts and crooked oak logs – were used to form the structural and seating elements. The project demonstrates three main findings: that high quality and complexity can be achieved and managed with a small, agile, and dispersed team with a high degree of trust and responsibility; that material waste streams, and small production environments can together construct complex timber structures; and that end-to-end digital integration is integral for a smooth design-to-assembly process. Each of these findings presents new opportunities in how timber construction projects might be developed in the future. However, they also present specific challenges that must be overcome.

There is a growing demand for wood for the building industry arising from wood's climate-friendly properties compared with other building materials (Mantau, 2015; Churkina *et al.*, 2020; Piccardo and Hughes, 2022). This emphasises the importance of reducing waste in timber production (Gustavsson *et al.*, 2006). Waste wood has the potential to lessen the impact of timber construction on the forest. However, timber presents complications in construction resulting from its anisotropic properties and features such as knots significantly affect the load-bearing capacity of construction elements (Dinwoodie, 2000). This project exemplifies how, through a shared and bottom-up approach between fabricators, consultants, and designers, these challenges can be mitigated.

Project context and design approach

Derived from the design of Marina Abramovic's Body and Mind Spa, the project is a continuation of the aspiration for a new spatial typology for health, body care, and social contemplation. The space encapsulates the different phases of nurturing the body through stages of presencing (Scharmer, 2009) and cleansing rituals. This typological exploration is continued in the design approach for the exhibition, although more heavily

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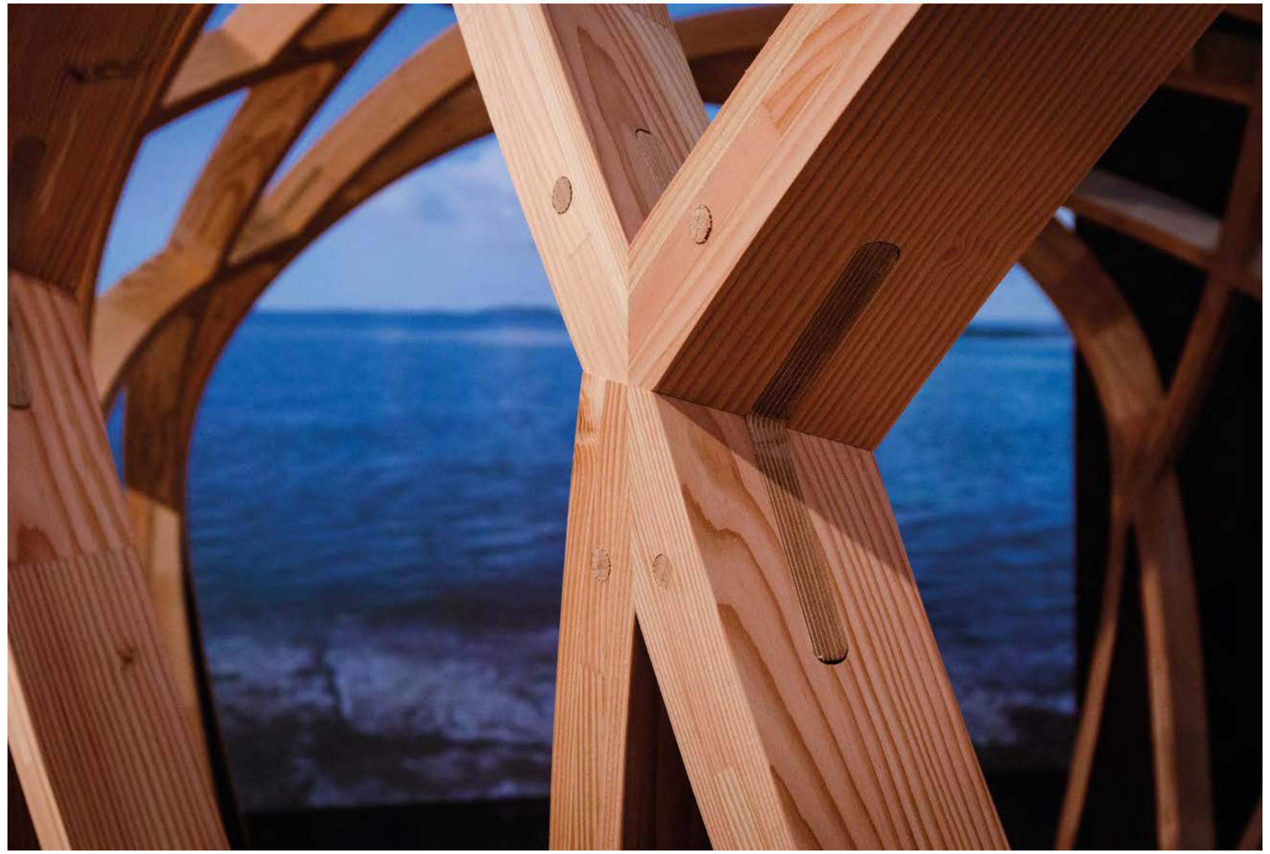

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weighted towards conveying a story of creation, material tactility, wonder, social interaction, and personal expression, within a smaller scale suitable for exhibition purposes.

The structure is composed as a shell with a clear directionality and spatial centre from the curving boundaries. The overall geometry blends walls and roof into each other in a continuous, perforated surface with a tapering height with apertures at both ends. Low seating along the two sides of the room is positioned to create zones for personal space while together activating the social space in between. The proportions of the space are carefully designed to capture the boundaries of personal contemplation and sharing an experience.

One key idea was to approach the project differently than previous architectural design projects: selecting the appropriate participants from existing networks, trusting them, and giving them freedom to shape the project with a holistic view. This resulted in a mix of team partners from industry and academia, and a wish to activate a thoroughly local value chain.

The core principles of the project were clearly established and shared: a wish to use only wood elements and connections, to challenge timber construction techniques by using reclaimed or rejected wood, and to use an integrated digital delivery model. In this way, the interdisciplinary team could operate assiduously and effectively within the compressed timeframe of the project.

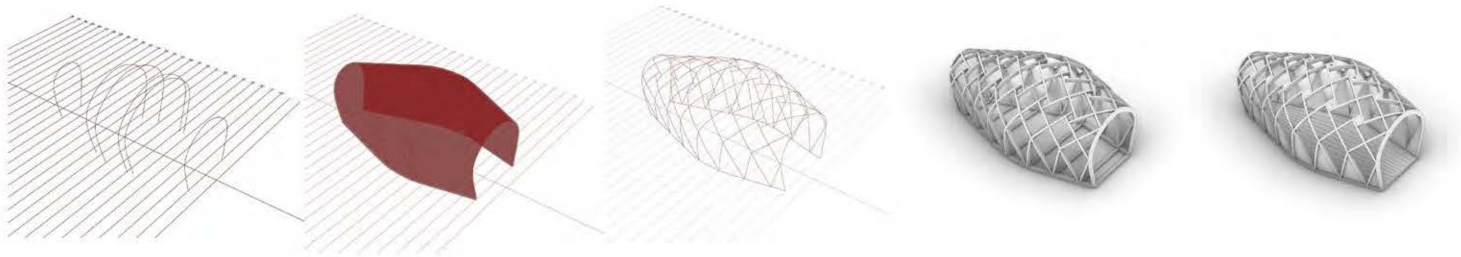
Digital modelling

In light of the tight timeline, an efficient method of generating and sharing information was required to minimise the translation and redundancy of information. A single model was therefore developed around which all discussions would happen, and that would gradually be built up with rising resolution of detail.

The general approach for the initial design model was using a master surface with projected beam centrelines, as in other well-known timber precedents (Scheurer *et al.*, 2013). This surface controlled the overall form and distribution of all the structural elements through a

1. The warm interior space of the *Marina Spa* prototype. © Tom Svilans.

2. A four-way joint with profiled connector plate, demonstrating the level of precision and coordination required in the information model. © Tom Svilans.



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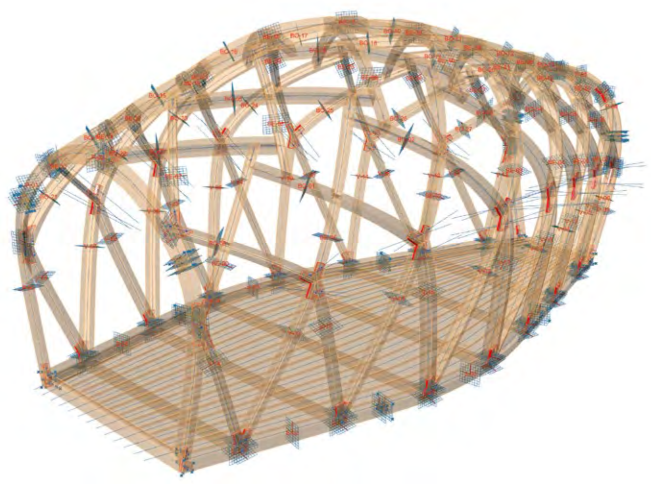

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3. The progression of the model in five stages: from coarse to finely resolved. © Helen and Hard Architects.

4. The digital model at the point of production, including all necessary connector plates and dowels. © Tom Svilans.

small set of parameters and allowed initial discussions to quickly zoom in on detailing, material quantities, and possible approaches to fabrication. The development of the model therefore traversed a hierarchy of resolution in roughly five stages: the initial project grid, the master surface, the interconnected element centrelines, the element volume representations, and the fully detailed elements. The first two stages consisted of laying out the primary gridlines and outer control curves of the project and creating the master surface. A lateral centreline defined the principal longitudinal axis of the structure and control curves were parametrically constructed along it. These were lofted to define the three-dimensional boundaries of the space and allocation of the structural system in ensuing steps.

In the third stage – the definition of the structural pattern and element centrelines – a reciprocal grid pattern was projected onto the master surface, with two rows of triangular modules – so-called V-columns – supporting the grid along each edge. The proportions of the grid were carefully adjusted to capture the initial design concepts and formative sketches.

The nature of all joint conditions – how many elements connect in one joint and in what way – was largely defined by this stage and informed the joint classification heuristic and solver in the subsequent stages.

The fourth stage – the definition of the element volumes and rough geometries – was crucial for communicating proportions, scale, and materiality across the team. Key decisions for how the element cross-sections should follow the master surface were made here. These seemingly simple decisions had substantial downstream impacts, as they decided how each element would be formed and fabricated. For instance, where binding the element cross-section orientations to the master surface would introduce twists to the element geometry, the elements were instead defined as planar, single-curved beams with profiled top and bottom faces, which followed the master surface. This greatly alleviated production complexity for the forming of each element, though at the cost of introducing geometric complexity at each joint. The differences in element orientation could then be resolved through detailed modelling within the specific production parameters. The fifth and final stage – the detailed production modelling – translated the element centrelines and joint conditions into fully detailed production geometry. The model needed to address both the composition of the elements and the specific geometry of each joint. The model therefore grew to accommodate these as a detail model of the segmented blanks as well as a family of parametrised joint models that could be assigned to the different joint conditions using previously developed methods for modelling timber structures (Svilans, 2021).

The segmented blank model provided the overall three-dimensional form of the blank and each segment, making it possible to inspect the joint conditions more carefully to understand how exactly the elements were intersecting and what types of joints would be appropriate. The model then had to accommodate the range of sizes of flooring off-cuts so that each segment could be feasibly machined from an off-cut. In this phase, close communication between the fabricator and model manager helped to refine this range and make the best mapping of material to blank segments. The family of joint models was driven by a mapping of all the unique joint conditions present in the structure and their variations, no matter how subtle. In the end, 114 machined timber elements were connected with 140 joints using nine unique joint types, each of which had to accommodate variations in parameters because of the constantly varying element geometry.

Development of each joint occurred through constant communication with the fabricator about what was possible to produce, what was economical, and what could be improved. Each joint was sketched out and gradually implemented as a fully parametrised model as the necessary parameters and constraints were better understood. These joint models represented the highest resolution and bottom-most scale of modelling in the project: each condition had to be considered carefully not only in terms of geometry and connection principles, but also in terms of assembly sequence, disassembly, logistics, tolerance, and reassembly. The intensity of this work was offset by the subsequent interchangeability of these models.

Integration of non-standard timber

The initial explorations of fabrication methods for the pavilion explored naturally crooked discarded oak as a construction material inspired by previous research by the Aarhus team (Larsen *et al.*, 2022).

Historically, architecture has utilised irregular tree parts for their specific properties or as functional replacements for straight parts, thereby incorporating natural tree growth into building culture (Prosser, 2020). Recently, approaches for using non-uniform materials have been explored. For instance, at the Architectural Association's Hooke Park campus (Mollica and Self, 2016) and Taubman College at the University of Michigan, it has been demonstrated how natural tree bifurcations can be utilised in construction using digital technology (Devadass *et al.*, 2016; Torghabehi *et al.*, 2018).

Using a local wood waste stream for the construction was seen as a resource opportunity and a way to involve and evolve existing research. The current study from Aarhus suggested a generalised method for engaging irregular logs. After receiving the crooked oak from the sawmill, the sawlogs are marked with reference points and registered with a three-dimensional scanner. A custom algorithm integrated into three-dimensional modelling

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software allows the crooked logs to be positioned into a designed geometry using a best-fit method. As such, the workflow connects the available resources to the design phase. Another set of algorithms can then translate the design into toolpaths and code for robotic machining of the components.

This research on wood waste-stream resources and algorithmic processing served as a valuable reflection of possible solutions for producing the prototype described in this paper. The use of discarded wood resources played an essential role in the construction strategy for the pavilion, and the use of discarded crooked oak and the three-dimensional scanning and fabrication workflow was directly used to inform the production of the seats for the pavilion.

The seats serve as points for rest inside the main construction of the pavilion. Each has a specific shape that fills the gap between the lower part of each row of columns. The geometries of the seats appear as coherent organic shapes but are based on surfaces wrapped around a stack of available discarded oak. Each material blank was laminated based on shapes, dimensions, fibre direction, and cracks and defects in the available wood. As such, the final design of the seats was developed through the negotiation of available material resources, the geometry of the main pavilion construction, and the intended architectural expression.

The segmented blank and approach to fabrication

The benefit of glue-laminated timber is that it can be assembled piecemeal into a highly variated and customised blank to respond to specific conditions. Here a material waste stream – timber off-cuts from flooring – was exploited to build up high-quality free-form beam elements. The floor manufacturer Dinesen AS supplied residual wood in the form of off-cuts from their floor production. As with the crooked oak, the use of this rejected material demonstrates an upcycling that creates value from a residual product without quality compromises for the final product.

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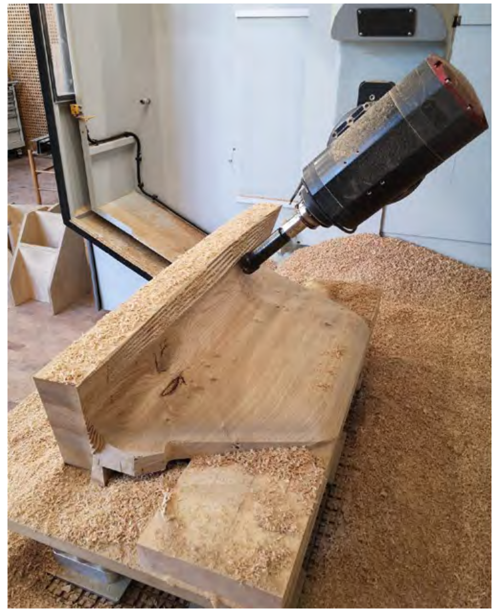

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5. The family of joint models accommodates all complex joint conditions in the free-form structure. © Helen and Hard Architects.

6. Boards are sawn from rejected crooked oak trees. © Niels Martin Larsen, Matthias Klith Hardarson and Anders Kruse Aagaard.

7. The seat geometry is precisely mapped onto the crooked oak boards and machined. © Niels Martin Larsen, Matthias Klith Hardarson and Anders Kruse Aagaard.

The unique character of this project meant that typical material procurement approaches were impractical. In larger industrial settings, the sorting and initial fabrication of timber takes place long before the final processing for specific beam elements. Developing the project in a joint forum therefore allowed a thorough engagement with the specific material allocation and its production in a small and flexible carpentry shop: from cutting raw wood to assembling the finished product. The 114 unique elements of the project were fabricated from more than 1000 individually cut pieces of reclaimed wood. By using piecemeal, segmented blanks for the construction elements, short pieces of reclaimed flooring off-cuts were specifically allocated to specific places in the final construction. The material was selected from this perspective, opening up a new level of material optimisation where specific properties could be incorporated locally into the individual construction elements as needed.

Because of the anisotropic properties of wood, the fibre direction of each segment needed to follow the curved geometry as closely as possible. The specific method – developed at Winther A/S – is to laminate the blank in staggered layers of short, straight pieces, where the deviation of the fibre direction from the curved shape depends on the fineness of the segmentation.

The method, in its simplicity, is all about controlling the location of the individual parts in relation to each other in an efficient and precise way. This is done with pre-drilled dowel holes, which align the segments together with a high degree of accuracy; once the dowels are hammered through, the individual pieces are pulled into their correct relative position. The advantage of the method is that no special equipment is required for gluing. However, it does necessitate precise machining of the segments beforehand.

The fabrication of the structural elements

The first step was to plane the reclaimed timber flooring off-cuts to the relevant thickness.

Individual segments were roughly cut in size according to cutting lists. The individual pieces were grouped according to which blank they were to be used for. The process offered a unique opportunity for material optimisation. The cutting lists were parametrically generated based on geometric requirements from the final construction and the nature of the material available, adjusted on-the-fly as material was received. Since everything was parametrically connected, these changes happened quickly, so that composition of the blanks could change without the structure itself changing.

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All the reclaimed pieces of wood used to form the curved blanks in the project were individually machined. The fabricator developed their parametrically controlled programme for curved elements which, based on an external shape of the blank and a desired division, generated partial programmes for the individual blank segments. The project required further development of this setup to incorporate arbitrarily curved forms instead of simple lines, arcs, and ellipses.

Second, to remain flexible and fast, a particular focus was placed on the data exchange. The segmented blank model therefore yielded all necessary data and parameters to generate input files that could be used by the fabricator for automatically generating production programmes.

After gluing, the blanks were planed before further processing. This ensured that all items had exactly the desired thickness. The curved blanks were finally processed with a 5-axis machining centre. The machining consisted of sawing, drilling, and multi-axis milling.

All work took place in a single continuous machining job without the workpiece having to be repositioned to maintain a high degree of accuracy. This was possible as a result of the prior close dialogue within the project group, between the architect, the model manager, and the machine programmer. The design of the joints had thus been adjusted according to the final processing, exemplifying an exceptionally valuable collaboration that delivered a precise result.

The connection plates between elements were made of birch plywood, chosen since the forces in the joints acted in multiple directions, requiring the cross-laminated reinforcement of plywood. In these connection nodes, elements with different orientations met. The plates were shaped so that their sides aligned with the sides of the elements, requiring five-axis machining.

Disassembly and reassembly

An important part of the design was that the construction should be able to be taken apart and rebuilt. The principle was demonstrated at a one-to-one scale. After the exhibition at DAC, the entire construction was taken down and reassembled at the Royal Danish Academy library. Only the wooden dowels for the connections were renewed. Everything else was used without modification, addition, or any kind of adaptation. After the second exhibition, it was taken down again and shipped to Norway to be erected for the third time.

Conclusion

The initiation, development, and execution of the project led to a series of pertinent discussions about the roles and compositions of project teams, the relationship between team participants and their respective knowledge domains, and the flexibility and resilience of the architectural design project. The success of the project could be posed as an argument for deregulation of the project team – towards more freedom and trust to explore different team compositions and roles – in the face of contractual constraints and concerns about risk and liability.

Here the approach to design was to establish and maintain a set of core values, around which the design unfolded and evolved. This malleability and adaptability to the team inputs allowed new opportunities – and perhaps surprises – to emerge through the process and discussion, all the while keeping the essence of the project intact. The resolution of the digital model was intertwined with the collaborative design process, as opposed to a rigid imposition from the designer. The difference ended up not being a compromise, but rather an enrichment, coming from understanding the entirety of the project and its essence by the project partners.

Materially, the project demonstrates a circular approach to complex timber construction, where waste streams can be deployed even in challenging and complex schemes that are typically reserved for only the highest-quality material inputs.

8. The reclaimed timber flooring off-cuts are inspected and sorted. © Morten Winther.

9. The segmented blanks are composed of short pieces of reclaimed timber. © Morten Winther.

10. The blanks are machined. Joints and surface profiles are cut out on a 5-axis machining centre. © Tom Svilans.

11 & 12. The detailed planning and modelling of the connector plates enabled an easy and accurate assembly process. © Tom Svilans.

13. The CNC-carved oak seats fitted between the V-columns. © Tom Svilans.

Acknowledgements

The project team consisted of Helen & Hard Architects (Siv Helene Stangeland, Reinhard Kropf, Håvard Auklend, Simon Aeschimann), Design-to-Production GmbH (Martin Antemann), the Royal Danish Academy (Tom Svilans), Aarhus Arkitektskole (Niels Martin Larsen, Anders Kruse Aagaard, Matthias Klith Hardarson), Creation Holz (Hermann Blumer and Christoph Meier), and Winther A/S (Morten Bandelow Winther). Special thanks to Dinesen Floors A/S and the Danish Architecture Centre (DAC).

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TOWARDS A HYBRID MODULAR CONSTRUCTION SYSTEM REUSING PRECAST CONCRETE COMPONENTS

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Introduction

The global building industry finds itself at a crossroads: while the demand for living spaces continues to surge in response to population growth and urbanisation, a critical resource problem is not merely on the horizon but is already in full effect. This juxtaposition of surging demand and finite resources underscores the pressing need for a paradigm shift in the way we approach construction. The building stock already in use represents the greatest resource available at present. Preserving load-bearing structures for as long as possible is the first priority for sustainable construction. Where preservation of a load-bearing structure is no longer possible, controlled deconstruction offers the opportunity to extend the life of individual load-bearing components by reusing them. Although this approach has been researched for several years, the reuse of load-bearing components has not yet entered common practice.

One reason is that the planning and construction processes in the building industry, as well as the underlying standards and regulations, are designed for the use of newly produced materials and components. Controlled deconstruction and the reuse of building components are not normatively regulated, nor are suitable deconstruction techniques and design strategies for reused structural components available.

In the post-industrial age, it is evident that we have to build differently. By drawing parallels to the serial and modular construction systems of the 1970s, we focus on the urgent need for sustainable, efficient, and environmentally responsible manufacturing technologies. While component exchanges and brokers already operating in the market are largely limited to the reuse of non-structural building components such as façade elements, floor coverings, elements of technical fittings, and interior furnishings, our approach pursues the reuse of structural concrete skeletons themselves. Since a large proportion of the resources used for building components, especially those made of mineral raw materials, are not reused after their first life cycle, the primary energy and engineering design work tied up in buildings is largely lost as a result.

As one solution, we focus on reconditioning and reusing existing concrete components. While there are regulations for the use of recycled concrete at the material level, there is still no approach to reuse at the component level. The

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focus of this paper is a building section serving as a 1:1 demonstrator. It is fabricated of reused and reconditioned concrete elements (REs), illustrating our actual digital process chain (Fig.2). For this purpose, an existing obsolete building structure was disassembled. Subsequently, the REs were obtained by reconditioning them at the Digital Building Fabrication Laboratory (DBFL) at the Technical University (TU) of Braunschweig. The novel underlying approach of reusing existing reinforced concrete components lies in recirculating locally installed, but no longer needed, components and reconditioning them uniformly into flexibly reusable components. These uniformed REs can be flexibly joined together to form new constructions. Newly designed reversible connections (Fig. 3) allow straightforward assembly and disassembly as well as enabling further reuse of the REs. Therefore, the lifetime of the existing components is maximised and REs can go through several life cycles. A life cycle assessment (LCA) accompanying the process enables evaluation of the ecological effects.

Background

For this proof-of-concept and the harvesting of suitable concrete components for the resulting demonstrator, German university buildings of the 1960s and 1970s were targeted specifically. The concrete skeleton structures of these buildings were often built using modular, precast construction systems. One of these modular and precast concrete construction systems is the *Darmstädter System*, which was designed at the request of the Hessian building authorities during the 1960s (Figs. 4, 5). The target was a flexible building system that would enable speedy extensions to the Darmstadt university campus to accommodate rising student numbers. The system draws ideas from the preceding and well-documented *Marburger System* but introduces fundamental optimisations, leading to significantly fewer components being needed during skeleton construction (Altmann and Arnold, 2001). Today, a similar situation in regard to building demand arises. But, while the climate crisis and resource scarcity were not pressing problems back then, it is imperative that we now meet the building demand with sustainable approaches to construction.

1. Selective disassembly by Bierfreund Beton-Bearbeitung using diamond-fitted concrete saws, harvesting concrete components for reconditioning and reuse. © Malcolm Unger, DDU, TU Darmstadt.

2. Assembled 1:1 demonstrator made from reconditioned concrete elements (REs). © Lukas Ledderose, ITE, TU Braunschweig.

3. Detail of a column-beam connection with its unique identification tag. Scan the QR code to watch a clip of the demonstrator. © ITE, TU Braunschweig.

4. Structural skeleton of the Faculty of Architecture building at TU Darmstadt's Lichtwiese campus during construction. © University Archive TU Darmstadt, UA Darmstadt F102 Nr. 463.

5. The Faculty of Achitecture was the first building on Lichtwiese campus to be built using the Darmstädter System. © University Archive TU Darmstadt, UA Darmstadt F102 Nr. 6742.

6. Deconstruction of the pedestrian bridge on Lichtwiese campus. © Malcolm Unger, DDU, TU Darmstadt.

7. Visualisation of the solution to an optimisation problem constrained by geometry and environmental impacts using mixed-integer programming. Green elements indicate components that can be manufactured from existing inventory, while blue components need to be produced from newly acquired raw materials. Statistical data on environmental impacts can be displayed via a heads-up display. The depicted scenario leads to a 53% reuse rate, predicting a 30% decrease in CO2e emissions compared with the conventional new production of all components.

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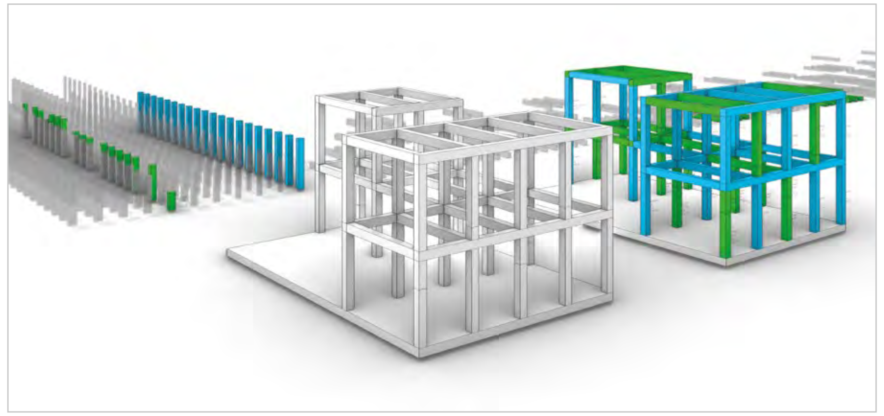

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To enable the reuse of these structural concrete components and to transition them into a modular and flexible construction system, a real-digital process chain is being used. This research was carried out as part of the *Precast Concrete Components 2.0 (Fertigteil 2.0)* research project with a team consisting of a range of academic as well as industrial partners. The individual steps of the real-digital process chain have been previously described in detail (Eschenbach *et al.*, 2023). The process starts with the digitisation of existing concrete components in obsolete buildings, using 3D-scanning technology from project partners FARO. Concrete components are then inspected using non-destructive performance assessment methods.

Suitable components are harvested and then brought to the DBFL, where they can be reconditioned by using robotic concrete sawing and milling (Fig. 6). On the digital side, the harvested component's geometry as well as all the associated metadata are catalogued in a component repository using IFC models in conjunction with a web-based database that can be queried using a standard REST API. A combinatorial optimisation software that is able to recombine the REs based on an input design was developed at the Digital Design Unit at TU Darmstadt, based on Brütting *et al.* (2020), integrating geometry, metadata, as well as LCA coefficients into the optimisation (Fig. 7). The entire process chain was monitored to quantify the environmental impact of the individual subprocesses by the department of Entwerfen und Nachhaltiges Bauen (ENB) of TU Darmstadt using a comprehensive LCA.

Harvesting

Through their modularity and systematic design, the precast concrete components stemming from the targeted university building structures are suitable candidates for our deconstruction and reuse process chain. In this context, the skeleton structures of multiple university buildings were evaluated and 3D scanned (Fig. 8). After evaluation, an obsolete pedestrian bridge at TU Darmstadt's Lichtwiese campus was chosen as the donor structure for this proof-of-concept. After the structure had been 3D scanned, key points for sawing were identified and the structure was disassembled using diamond-fitted saws (Fig. 1). Components were kept as large as possible to avoid limitations during recombination and reconditioning. This is essential to be able to reuse as much of the original structural substance as possible.

Once the structure had been disassembled, the individual components were transported to the DBFL in Braunschweig via heavy haulage. The environmental impact of the sawing and disassembly processes as well as the transport to Braunschweig were recorded and quantified, and informed the LCA.

Design of the demonstrator

The guiding principle in the design of the demonstrator was to develop a prototypical unit as a fragment of a larger building structure that is both scalable and changeable by varying its dimensions and proportions, and that can be combined with other building systems in the sense of a hybrid construction method (Fig. 9).

The demonstrator consists of ten linear REs that have their origin in pieces sawn out at the demolition site and have been transformed into new, fully fledged prefabricated elements by refurbishing them and adding connection details (Fig. 10).

In addition to retaining their original function in the structure, the transformation of the components into REs also offers the possibility of assigning new functions. In this way, the demonstrator was designed using columns as foundations, although their former function was as beams and bridge piers.

The key element is therefore a linear component that is essentially made up of three components (Fig. 11). The body of reused concrete components forms the central part. In order to define the suitability of the new precast elements, it is necessary to know not only the properties of this body in terms of external geometry, but also the type, content, and location of reinforcement elements. There are basically two possibilities for determining the existing reinforcement. Either there is sufficient documentation in the original execution plans, or the determination of the reinforcement has to be done subsequently by sectional views and detection systems. Further investigations of the concrete matrix by compression tests and measurements of the existing carbonation serve as a detailed comprehensive determination of the structural properties of the component. Harvested components that do not qualify for the new application can be strengthened – e.g., by carbon fibre reinforced plastic lamellae.

The body was cast by means of swelling mortar into steel sleeves, which are made of hot-finished structural steel hollow sections (HSS) from E355 (1.0580) and closed with welded-in end caps. The performance of these sleeve joints as well as pull-out tests of threaded rods subsequently bonded into aged concrete were previously investigated experimentally in test series and validated numerically. After curing this adapter of swelling mortar, the bond of

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the end caps to the body is strengthened with anchor bolts. A projection of the HSS beyond the caps allows both a simple and quick screw connection of the steel joints to each other and the flexible and even subsequent drilling of holes for various connections.

The use of HSS brings several advantages. On the one hand, they are standardised components available in numerous cross-sections and are relatively inexpensive. On the other hand, in combination with a cast adapter made of swelling mortar, they allow the use of a wide variety of different and irregular cross-sections of the body. Thus, in the case of our demonstrator, the slightly trapezoidal cross-section of the reinforced concrete girders from the Darmstadt bridge could also be cast into the rectangular HSS and thus used as uniformed REs.

Joining technique

At the core of the design of new harvested-element structural systems, the desired connections should be robust, capable of transmitting forces in all degrees of freedom (DoF), standardised, cost-effective, and adaptable in terms of dimensions and force capacity. The joints developed here meet all of the above criteria. These tube joints exhibit high flexural and shear strength in the experimental tests. Further, the advantages of these joints are:

1. Free location allocation: They can be placed in any part of the beam and columns. Therefore, the elements can be connected in parts of the structure with lower forces. Likewise, by using different numbers and lengths, a long beam can be made by connecting several short elements.

8. The structural components, columns and beams were identified within 3D scans of the buildings. © Anna Braumann, Lucia Martinovic, Nastassia Sysoyeva, DDU, TU Darmstadt.

9. Built demonstrator as a fragment of a larger building structure.

10. Production line of all REs used as columns and beams in the demonstrator.

11. Composition of an RE.

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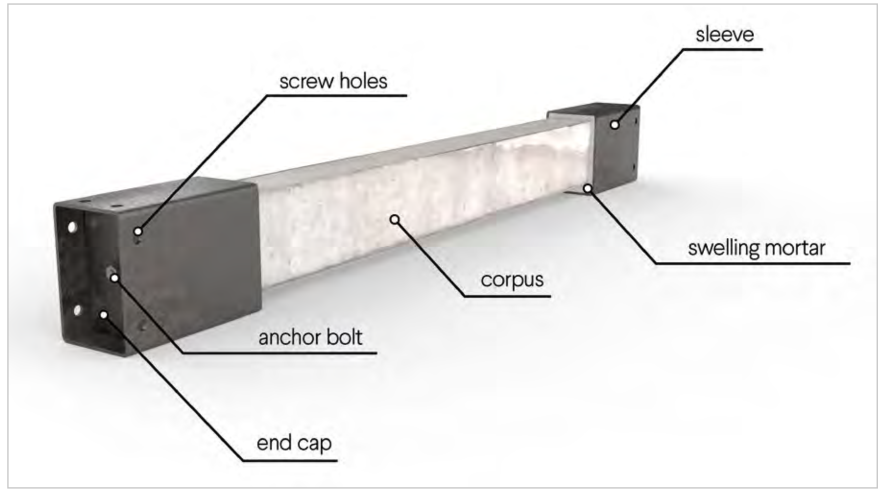

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2. Adjustable geometry that offers different mounting angles and can change its capacity according to the requirements of the connected elements (e.g., by adjusting the wall thicknesses and the height of the sleeves).
3. Production of rigid as well as flexible frame systems: Unlike typical concrete buildings with only rigid connections, a flexible frame can be created by reusing the old elements connected by this connection to reduce the forces and dimensions of the elements. Accordingly, a simple bracing system similar to a steel structure can also be added. The former case, shown in the demonstrator, allows a particularly simple assembly process (Fig. 12).

Fabrication of reconditioned elements

For the production of the new precast elements, different manufacturing and processing methods were used at different locations. While the concrete sawing operations at the demolition site in Darmstadt were carried out manually or semi-automatically by a company specialising in the dismantling of concrete structures, the precise cutting of the concrete elements to the required length was carried out by CNC saws at the DBF. In a first step, superfluous structural elements such as the reinforcement connecting the beams to cast-in-place concrete slabs and separating foils were removed. Subsequently, the geometry of the individual elements was recorded with the help of 3D scans and the quantity type and position of the reinforcement was detected. After assigning the individual concrete elements to their new functions as columns, beams, and foundations required in the design of the demonstrator, they were cut to the exact length, aiming to create the least possible waste (Fig. 13).

Structural modification of aging concrete

When reusing reinforced concrete, three different aspects must be regarded: possible changes to standard calculation methods, the influences of aging on the old material, and the approaches to reassembling and connecting individual elements.

The reused beams for the demonstrator meet the requirements and considerations, such as the allowed amount of the longitudinal rebars in section (3 x ø18mm), the dimension limitations (0.14-0.16 × 0.24m), and the permissible distances between the stirrups (0.15m) (ACI Committee, 2008).

While concrete, by and large, does not lose its strength without chemical attack or damage, aging influences in

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rebar are harmful, including corrosion as well as changes in production technology and, accordingly, differences in yield (Y) and ultimate stress compared with today's technology. Through the last six decades, rebars with yield strengths from 275 to 500MPa were produced (Munter and Lume, 2018). In addition, the diameter of the rebar decreases due to corrosion (Duffó *et al.*, 2004), resulting in an average reduction of 6mm² per rebar section after 60 years for an 18mm rebar. Severe rust also has an impact on the cohesion between rebar and concrete.

Taking into account the influences of these two effects, the 60-year-old beams that were used show 32% lower bending capacity and 13% lower shear resistance compared to brand new ones.

Life cycle assessment

The ENB at TU Darmstadt quantifies the greenhouse gas emissions and resource consumption of the REs in comparison to recycled and conventional concrete. The principal material flow shows the proportions of material from stock and new raw material that can be used for 1m³ of final concrete product. A LCA based on DIN EN ISO 14040 (2021) and DIN EN 15804 (2022) is used to calculate greenhouse gas emissions. All energy and material flows that are generated by the processes of reuse are recorded. The system boundary includes harvesting of stock resources, transporting, processing, and assembling into a new structure. The functional unit chosen is a 1m³ component of the newly produced concrete structure (including steel connections). All energy and material flows included in the balance relate to this component as the final product. For comparison, the greenhouse gas emissions for the REs are balanced with emissions from recycled concrete elements (RC) and conventional concrete elements (CN). The input data for this are based on studies by Heyn and Mettke (2010) and the greenhouse gas emissions are determined based on the described inputs and the ecological database (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, 2023).

The results of the LCA show that the greenhouse gas emissions of the reused component are about 65% lower than those of recycled concrete or conventional concrete. This is particularly due to the production of new materials: the production of cement in recycled as well as conventional concrete causes high emissions. Recycled concrete can profit more from saving resources than from greenhouse gas emissions. The highest share of emissions of the REs comes from the newly manufactured steel-connecting nodes. The share of reconditioning is comparatively high for the REs, which is due to the processing of the components (sawing, chiseling, etc.). A sensitivity analysis shows that, under the selected model conditions, the REs in a transport radius of about 700km have lower emissions than conventionally produced concrete elements on site.

Gaining of knowledge and outlook

The evaluation of the harvesting process shows that preparation of the individual cuts is the most time-consuming step, as sawing equipment and a crane must be set up precisely beforehand. Once the preparation is complete, sawing the components is straightforward.

12. Assembly of the 1:1 demonstrator structure using the developed standardised and reversible connection details. © Tjark Spille, ITE, TU Braunschweig.

13. CNC cutting of a former column in the DBFL for reuse as RE.

As such, the time-consuming harvesting process can be improved significantly through specialised equipment and process optimisation, and even more so through automation of the process (Lee *et al.*, 2022).

In this study, about 72% of the harvested stock resources for the concrete structure could be reused. A higher rate of material utilisation would improve the LCA and could be achieved through early and accurate stock assessment as well as process and planning optimisation. However, unforeseen obstacles arising from the inventory materiality (e.g., pollutants, corrosion) will not be preventable when reusing entire components. Since the production of steel is energy-intensive, optimisation of the joining nodes (e.g., reduction of quantity, change of material, other types of joining) can also improve the balance.

In addition to the subtractive machining of harvested components by CNC sawing and milling shown here, the DBFL will be expanded in the near future to include a 5-axis water jet cutting system that will enable complex cuts of up to 40cm depth even in highly reinforced concrete and many other building materials. In addition, the TU Braunschweig's Institute of Structural Design (ITE) is researching techniques for the subsequent strengthening of structural components by means of robot-assisted reinforcement layers.

The project clearly shows that the fabrication process needs to be implemented into a larger real-digital process chain, from digitising existing building stock to disassembly, design, matchmaking, digital fabrication, and assembly, all accompanied by a constant LCA. Future work needs to embrace additional stakeholders such as (de-)construction companies, digital marketplace developers and regulatory institutions.

Many buildings stemming from the targeted period of the 1960s and 1970s are now in need of redevelopment or have become obsolete. The question of how to deal with this anthropogenic stock needs to be answered to match the European targets for reducing CO2 emissions by 55% by 2030. The authors conclude that transitioning their individual components into a novel, similarly flexible and prefabricated construction system is one viable trajectory.

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PROTOTYPING NEW SCENARIOS FOR FABRICATING STRUCTURAL COMPONENTS FROM RECLAIMED TIMBER

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Introduction

As building practices shift towards bio-based materials, they must also strive to understand the limitations to the extent to which woody biomass can alleviate the destructive effects of post-industrial material procurement and production. Through the development of *Wood ReFramed*, a pavilion imagined as a 1:1 building segment, this paper investigates novel methods for approaching structural applications with reclaimed timber.

Relatively established concepts of resource flow, such as the Circular Economy (CE) and Biomass Cascading (BC), illustrate strategies for enabling greater material efficiency. They propose ecologies organised across technological and biological spheres to create extended material lifetimes, through multiple applications, and portray modes of cyclical matter flows. However, they remain abstracted from the contexts in which material flows take place, neglecting the imperative role of design, and how this engages with prevailing infrastructures for realising alternatives to our current wasteful paradigm.

This study explores actualising the CE and BC theories, by rehearsing the necessary steps required for developing large-scale structures from reclaimed timber. Seeking alternatives to recycling methods of homogenisation and premature incineration, the project maintains timber in its solid form, tackling the associated challenges and uncovering the potential virtues. Through the design and development of the build project *Wood ReFramed*, the paper investigates the following questions:

- How might we design structural components to offer extended lifetimes for reclaimed timber in new material flows?
- How can novel methods interface across existing design and fabrication contexts to increase traction and uptake across industries?

By intercepting what would likely be a transition of material into fuel, the design process engages directly with alternative modes of material sourcing. As an alternative to traditional project timelines, the process interacts with the temporal nature of reclaimed material availability. This paper presents the viability of incorporating reclaimed material in structural components, explored through design, fabrication, and assembly.

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State of the art

Recent efforts to assimilate reclaimed timber in structural applications are limited primarily to research investigations. These can be divided into studies that have prioritised a high level of technical assessment, and studies that explore novel systems. The former has typically sought to integrate reclaimed material into existing engineered wood product technologies, such as glulam and CLT (cross-laminated timber) (Rose *et al.*, 2018; Risse *et al.*, 2019). The latter group has investigated broader aspects of reuse, such as locality, and specific relationships between constrained material stock and morphology (Nordby *et al.*, 2014; Bergsagel and Heisel, 2023; Ruan *et al.*, 2023).

The advantage of operating within existing taxonomies is the opportunity to integrate within current structural typologies. However, the studies mentioned demonstrate low material yields (~20%), because of the demands these systems have on uniform material cross-sections and rejection of *defects*. The latter studies offer new methods and material flows, but, through their novelty, are isolated from existing production and building systems.

This research aims to provoke an affinity between the two approaches, investigating the integration of new material flows in existing systems combined with the broader ecologies necessary for developing structural typologies from reclaimed timber.

A structural typology for reclaimed timber

Investigations seeking synergies between the parameters associated with reclaimed timber and structural components has found potential in the patent developed by Hilding Brosenius (Browne *et al.*, 2022). Brosenius's original 'HB Beam' was manufactured in microfactories during the mid-20th century and was applied to a range of building typologies from housing to long-span aircraft hangers (Brosenius, 1990). When applied to a varied stock of reclaimed timber, yields as high as 70% have been reported, arising through reduced processing demands and the ability to include a wider variety of material traits (Browne, 2023).

Structural components in timber comprising multiple parts mechanically fastened together are familiar in traditional truss and frame structures. These were common in a time when materials were costly, and prior to reliable chemical adhesives. However, they still have relevance today, and not only from the perspective of material utilisation.

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Working with waste timber can initiate concerns regarding structural safety, as for those working within the European Union's legislative frameworks it is challenging to assess the structural quality of secondary timber according to its standards. However, it is feasible to design a level of redundancy within a component, where through 'over-structuring' it is possible to utilise materials that would otherwise be discarded. This is akin to strategies employed for global structures to mitigate the possibility for disproportionate collapse. With components containing multiple parts performing individually, a designed progressive brittle failure mode can emulate the ideal ductile failures made possible with steel components and connections. Furthermore, in part-based components,

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1. View of the horizontal beams with steel saddles and tension rods to carry the seating area below. © Sara Lohse.

2. Suspending the reclaimed glulam seating onto the tension rods. © Nana Reimers.

3. Inserting the tension rods into the reclaimed glulam seating elements. © Nana Reimers.

4. *Wood ReFramed* on display at the congress. © Sara Lohse.

the individual elements can be strategically allocated in response to performance and spatial requirements.

As whole components that maintain the elemental identity of their parts, timber species and surface treatments – in all their aesthetic diversity – remain exposed. This offers an opportunity that becomes especially relevant to post-consumer timber, which has been formed through interaction with multiple agencies over time.

Geometry / Topology / Material

The proposed component explores the relationship between geometry, topology, and the availability of material forms. Material, fabrication, and design constraints can be simultaneously evaluated to define optimal component outcomes.

The exterior component geometry is simply described with eight Cartesian coordinates, resembling conventional design space environments and building information norms. Here, rectilinear exteriors are exemplified for their genericness and interchangeability with substitutable components in circumstances where reclaimed material is unavailable. Repetitive geometries pre-empt direct reuse potential, as contemporary examples owe their success to the availability of enough similar components. Within this design space, a determined quantity of material can be allocated based on externalities such as loads, supports, and masked enclaves. The simple two-dimensional topology analysis also defines tension and compression regions. This allocation can be translated into discrete lines, representative of web members, and a boundary representative of upper and lower chords.

The inherited forms of reclaimed material encompass two main variables: the intricate deformations occurring naturally, such as cupping, bowing, and twisting, and the cross-section categories informed by sawmill standards. In the project, these variations are not recorded, described, or modelled. Instead, a domain of cross-sections that can be utilised within the system is defined, significantly reducing the potential complexities arising from part tracking and configuration.

Unrefined parametric relationships

The relationship between discrete lines and varied material leads to an unrefined parametric relationship between material availability and component performance. Web elements are cut with uniform lengths, enabling constant interfacing with the beam system, and avoiding excessive removal of timber. The representation of component topology is simplified, and actual component geometry is only represented in the built form.

As well as allocation, structural assessments using finite element analysis can define optimum material cross-sections for all component parts. While this could enable an especially sensitive relationship between design, material form, and material performance, it would likely also contribute to a reduction in material effectiveness due to increased off-cut. In an unrefined relationship, over-structuring leads to a higher utilisation of input material. Efforts to be more specific about property allocation should work with methods for gathering the structural capacity of material stock. For example, non-destructive test methods could be used to assign grading values to each of the parts, subsequently informing their arrangement within a component.

Joints

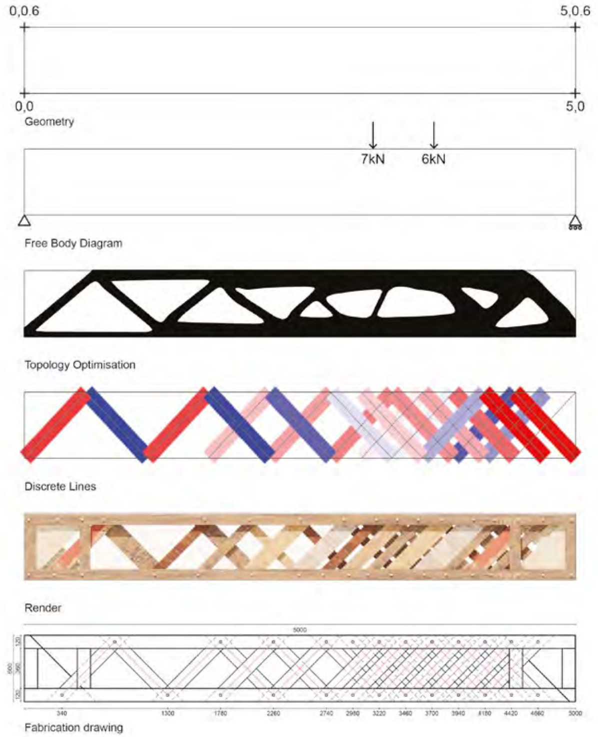
In this project, multi-shear mechanical joints are favoured over adhesives for their ability to connect parts with uneven surfaces. They must, however, be solved intelligently to avoid excessive use of high-impact materials such as steel. Two types of hardwood birch dowels are tested, both with a starting diameter of 19mm, with one set threaded to have an inner diameter of 16mm. Both are effective for multi-shear connections; however, threaded dowels are also capable of locking elements along the dowel's longitudinal axis. Three specimens of each dowel type were tested according to ISO 6891. The unthreaded dowels show a clear advantage in both stiffness and overall capacity, with an elastic limit of 6kN. The unthreaded dowels, however, had an elastic capacity of 4kN.

Wood ReFramed

Wood ReFramed was initiated as a 1:1 build project to test the scaling and production of the structural components in collaboration with industry actors. The project is conceived as a building segment, referencing a domain of scales from small buildings to high-rise typologies. The box-like geometry intends to communicate how disordered inventories of reclaimed timber can assimilate with construction conventions. Furthermore, all angles in the project are 45° or 90°, simplifying design and production, as well as offering optimum tension and compression relationships for truss-type structures.

Defining load cases

To test the component typology and methods, realistic building scale loads were a necessary facet for the project. The 15 components are uniform in external geometry, yet each feature a varied distribution and quantity of web elements. This material allocation is mostly informed by structural performance, determined by the specific load cases for each of the frames. To design unique load cases for the repeated frames, a seating area constructed from reclaimed glulam is suspended at 45°. In plan, the centre of gravity lines of the seating steps intersect with the centrelines of the beams, defining the location of suspension brackets. The load case is defined based on an occupancy of 4kN per m² plus the self-weight of the glulam steps, leading to ten point-loads ranging from 1 to 9kN. The maximum force in the web members is calculated to be 4.5kN, well within the elastic range of the regular dowels, but on the upper limit of the threaded dowels. Therefore, regular dowels were applied to shear connections, and threaded dowels are located intermittently to secure assembly.



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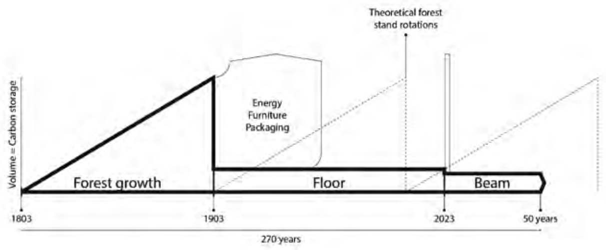

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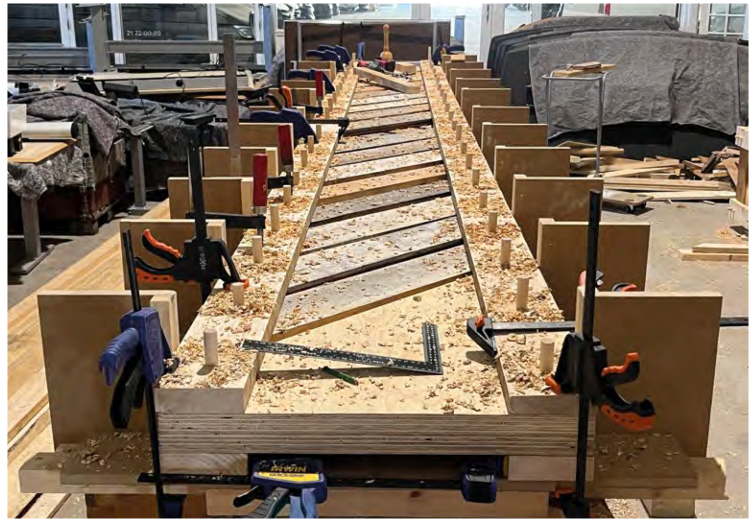
5. Occupying a rectilinear boundary with different modes of representation.

6. Estimated material timeline spanning 270 years.



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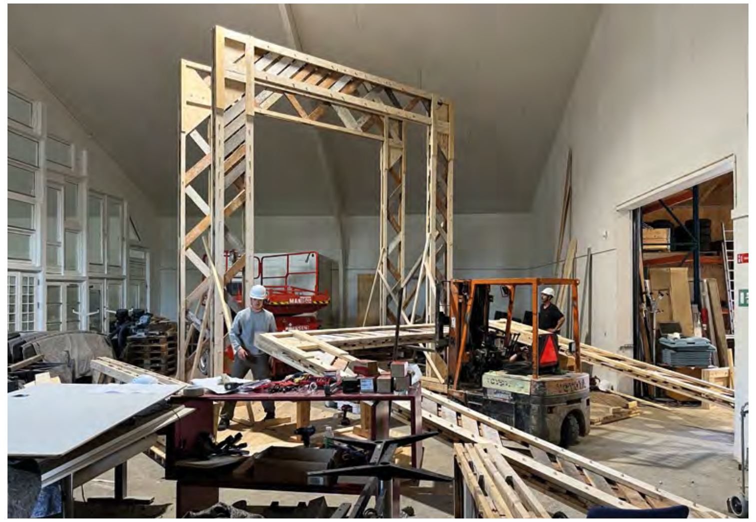

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7. Beam during fabrication: assembled component before being released from the jig.

8. Production space during test assembly.

Material search criteria

As the project depends on an uncommon material source, a search criterion was developed, informed by the architectural, structural, and detailed design of *Wood ReFramed*.

Danish organisations such as GreenDozer and Genbyg are developing systematic waste collection and sorting strategies intended for use other than recycling. Furthermore, companies such as a:gain are designing new supply chains and stakeholder relations to create building products from established waste streams. However, economic, legislative, and practical constraints remain, leading to issues in valuing materials with high potential. Demolition contractors are critically positioned with access to large quantities of post-consumer material. However, the temporal nature of demolition projects requires them to make quick estimates of a material's value, before deciding whether to invest in careful dismantling, transport, and storage. These speculations traverse a broad market, with many material forms and types passing through their activities.

Jensen Genbrug, the demolition contractor collaborating on this project, at present sells 90% of salvaged materials to private customers and is developing its business to be more attractive to industry. Together with them, a search criterion defining basic material requirements for the project was developed. These key parameters were sent in visual form to all demolition sites in the Copenhagen area for workers to quickly identify compatibility. Minimum lengths, an ideal domain of cross-section, as well as contaminants to be avoided, such as foam, were described. The resulting stock received no formalised structural verification. However, a visual assessment based on the INSTA Nordic standard for timber grading was used to confidently assume design values based on a minimum of C14. Future studies that investigate an enhanced strategic relationship between mechanical properties and component performance could enable more specificity while maintaining the advantages of semi-discrete parts.

In a future where prototypical fringe practices become implemented in everyday projects, modes of secondary material sourcing must operate across significantly longer and more predictable timelines than exemplified here. Current research into the availability of wood within existing structures can quantify usable quantities that will become available post demolition (Kaasalainen *et al.*, 2023). These data sets offer a broader understanding of timber availability, which includes the material already in use. In the same way that the future availability of lumber is today calculated based on forest stand rotations, a holistic assessment can include regions of existing timber buildings where their construction types and estimated lifespan can be included in an overall assessment of timber available for construction.

Adding regional sensitivity to the timber quantities and forms for future construction hints at (new) vernacular architectures. Anthropogenic resources may become synonymous with the terrestrial material availability that has informed the building culture around traditional settlements. The new industries that emerge as a result of valuing post-consumer material will need to be supported by legislative standards that can operate across domains of material parameters, rather than uniform, repetitive requirements.

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Fabrication, assembly, and inhabitation

Many projects employing digital design to develop specific relationships between materials and performance end up with large quantities of unique parts. In this project, adhering to the semi-discrete system of web elements mitigated challenges around traceability, as the variation present in the web elements does not affect their distribution or organisation.

A single jig resembling the precise exterior geometry was used for producing all 15 components. The various parts included in the beam geometrically deviate from the way they are understood in modelling. Slight *bowing* was particularly present in many of the chords, which would traditionally be processed out of individual boards. In this case, during assembly, the beam parts were clamped to the jig as a constant reference geometry for all the components. The layout of the component parts could be described in a simple drawing, with web element placement in a limited number of discrete locations.

The waste timber beams proved significantly more manoeuvrable than the secondary glulams as a result of the strategic allocation of material. Even the examples filled with web elements are half as dense as glulams based on outermost dimensions. This *lightness* potentially enables easier building assembly, and a reduction in foundation magnitude. During assembly, components could be identified by comparing their appearance with project drawings. This suggests that in larger-scale projects with multiple component types of the same outer geometry, individuals could be differentiated and assembled accordingly.

Material origins and futures

As the normative LCA practices draw a system boundary occupying a period from resource extraction to the end of a building's lifetime, they offer a limited representation of material origins. These practices also neglect the former life of secondary materials, and the many interactions that create material conditions are withheld from the assessment of a material's value.

As an investigation into material flow, the notion of components as static objects must be challenged. Uncovering the lines of origin that have defined their emergence are key for understanding the broader ecology of building and depicting the larger terrestrial and cultural consequences of making architecture.

Based on anecdotal evidence from the demolition contractor, we can estimate the material's provenance and geographic movement since its emergence. Depicting the duration of time a material has occupied, we learn that 'new' components are merely convergences of existing matter, convergences informed by a negotiation between the traits of latent material, design, function, and performance. Fig. 6 describes the possible flow of matter as it transitions from emergence to various functions. The y-axis represents material volume, a key metric for assessing effective utilisation and anthropogenic carbon storage. Here, we also see the significant material losses typical during forest harvesting, as only 20% of material is applied to lumber production. This study succeeds in utilising an estimated 75% during the production of web elements.

9. Preparing fabrication jig for the production of all frame components. © Thomas Sinding.

10. Close-up of secondary timber boards. © Xan Browne.

The total distance from demolition site to production site, to exhibition site was less than 100km, demonstrating a significantly shorter supply chain than if virgin materials had been used. As material lifetimes map against forest regeneration, we can start to assess the renewability of material paradigms, as opposed to defining materials as renewable in themselves.

Where material flow is concerned, the components are neither a beginning nor an end. However, determining material availability for future scenarios relies on speculation. Fig. 6 references the 50-year lifespan that is given in the Danish (LCA) standard. Material longevity is integrated into the component's design and is a key aspect for effective cascading. Although the components are designed with a very specific function in mind, the web elements retain the ability to be reorganised, removed, or added to. Reconfigurations may respond to changing functional demands, repair, or disassembly. As timber-only structures, the concentration of material type is homogeneous, and reversible timber joints allow for the separation of wood species. Situating materials in timeframes that are longer than typical building lifetimes raises the question of how we might redesign and reclaim in new methods for creating architecture for the future.

Conclusion

This research investigates potential avenues for reclaimed timber's role in load-bearing structures at the building scale. Exploring new component typologies that are situated within the temporal nature of timber's existence aims to offer insight into the many durations the material can occupy. Determining these durations is a fragile process, as we realise the many sectors that utilise wood, and the need for sufficient material regeneration periods to enable renewable practices. Working across simple Cartesian geometry, performance-informed topology, and inherited material forms intends to enable new matter flows to assimilate into existing practices. These demonstrate that novel methods can integrate with current procedures and support the stakeholders who are positioned to contribute with additional effective resource scenarios.

Optimised buildings are not only about the material quantities they contain, but are assessed in conjunction with a wider ecology of material, production, location, application, and future. Maximising the amount of timber in construction requires a combination of utilising material that is currently undervalued, and designing structures that enable materials to have a life beyond the building, whether that be through long-term component life, or through multiple component lifetimes. The methods presented here intend to correspond holistically with that dialogue, offering insights for better timber practices in the future.

Acknowledgements

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PRŌTÓPLASTO
A DISCRETE ROOF-COLUMN SYSTEM WITH HOLLOW-CORE 3D PRINTING AND BESPOKE SPACE FRAMES

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Prōtóplasto, an ultra-lightweight plastic media installation, introduces the novel process of hollow-core 3D printing (HC3DP) to upscale polymer 3D printing (3DP) for architecture, and the novel method of support-free assembly of bespoke space frames (SF) through the geometric articulation of 3DP joints.

The pavilion is a light installation in an upcoming innovation hub in Switzerland and consists entirely of hollow plastic elements produced through 3DP and off-the-shelf parts (Fig. 1). Learning from nature, creating hollow structures paired with smart geometric articulation, one can achieve architectural height and volume with minimum material and weight. The design and fabrication of the pavilion was formulated as a studio brief for the MAS in Architecture and Digital Fabrication (MAS DFAB) at ETH Zurich.

Contextualising the research on 3DP plastics in architecture to discrete, deconstructable, and reconfigurable systems with different properties provides new ground for exploration in 3DP architecture, which until recently was envisioned as predominantly monomaterial and monolithic. The mixed use of processes and systems in this project finds unity in its expression through plastic materials and allows for the exploration of a more playful architecture towards an ephemeral definition of space freed from the constraints of massive, permanent materials used in construction.

Plastic architecture in the digital age

The introduction of plastics in architecture dates to the beginning of the 20th century, when the fascination of architects with this synthetic material sparked the imagination of 'featherweight' houses, in the words of Fuller (2008, p.9). The lightweight quality of the material and high strength-to-weight ratio provided b-products like fibreglass embodied the utopian image of cheap, transportable, bespoke, and organic buildings that could be accessible to all. The acceptance of synthetic materials as the future of architecture in the 1960s provided further ground for modular buildings that would replace concrete and steel. While the fascination with the material soon transferred to light membranes and tensile structures still used today, the production of entire building components out of plastics was put to rest until recent years, when 3DP and especially material extrusion (ME) provided a cost-effective method accessible to all for creating customisable plastic parts of large dimensions using

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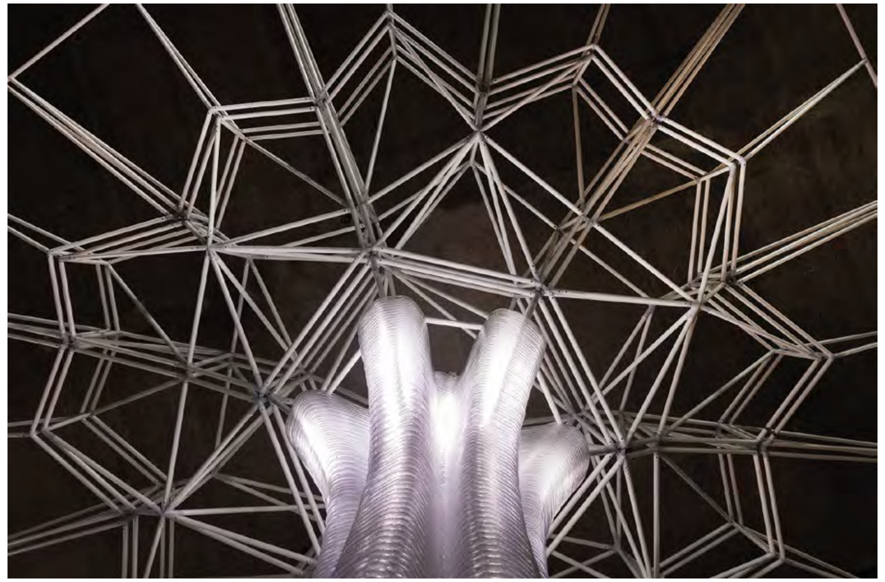
thermoplastic feedstock without moulds or falsework (Vicente *et al.*, 2023).

Contemporary technological advancements have not only eased and democratised the use of plastics through 3DP but present new opportunities to imagine the 'new' plastic architecture in the digital era. Furthermore, the use of synthetic plastics presents an additional material resource that relies on the chemical by-products of fossil fuel refinement processes (Center for International Environmental Law, 2017), thus maximising the use and value of the resources that are already extracted. Their recyclability can be achieved with less consumed energy than other construction materials like metals or concrete, because of their low melting point, especially when not formed into composites. Their reuse is achievable through the durability of many synthetic polymers. In the future, the growing use of bioplastics can be seen as an alternative to synthetic ones as the extraction of fossil fuels is slowly eliminated.

With this project, the authors examine anew principles of lightness, modularity, and temporality in architecture with the mixed use of manufacturing methods and plastics. The goal is to explore new architectural aesthetics, novel production methods promoting material savings, methods for (dis)assembly, and geometric articulation for modular components, as well as pushing the limits of light construction to Fuller's notion of 'featherweight'.

Towards discrete prefabricated architecture

Digital prefabrication of discrete elements is a core principle of *Prōtóplasto* that the authors believe is relevant for the adoption of digital fabrication techniques



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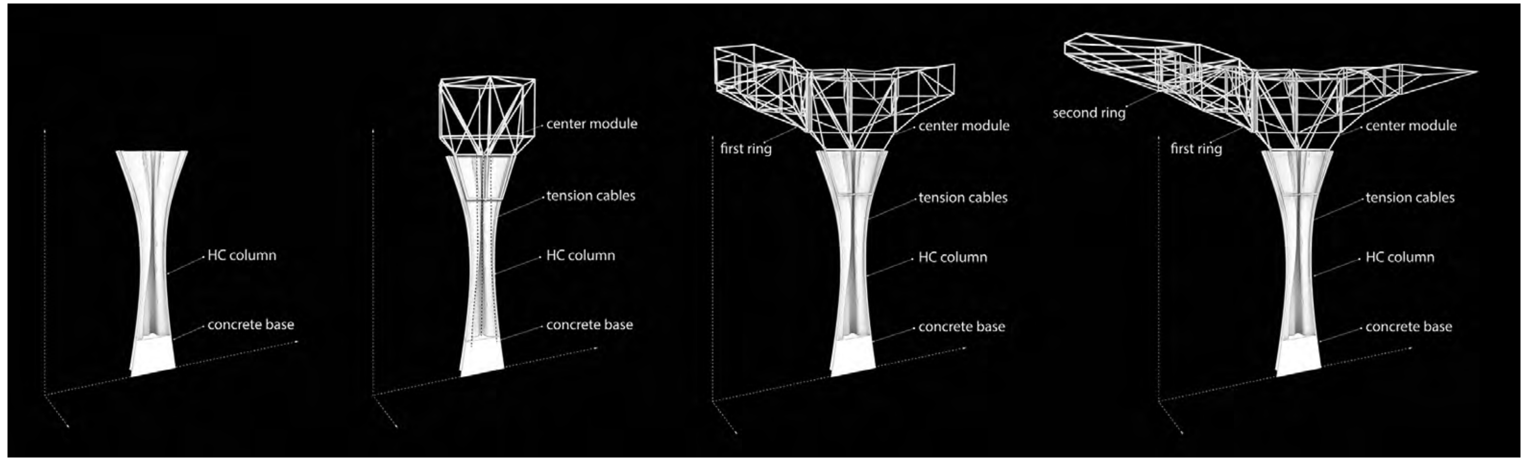
in construction. In this spirit, the most appropriate techniques, materials, and methods are identified and employed for the different parts of the constructive system. Macroscopically, the structure is a slab–column pair for which two systems are combined to deliver the different properties required for those two elements in the most efficient manner: large-scale ME and 3DP-enabled SFs. Although technical advancements in 3DP have achieved a significant increase in build volume, contemporary approaches result in heavy, material-intense elements. The expanding size of 3DP machines has alluded to the continuous in-situ fabrication of entire buildings. Nevertheless, the fabrication of vertical and horizontal elements in a continuous process at an



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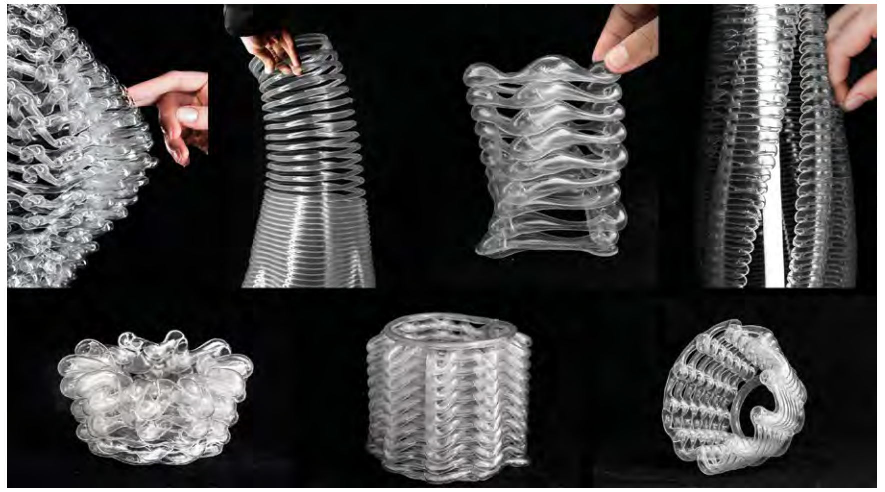

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1. Prōtóplasto exhibition. © Andrei Jipa, DBT.

2. Transition between column and roof structure. © Andrei Jipa, DBT.

3. Assembly scheme. © Matthias Leschok, DBT.

4. Prototype of concrete feet, SCC cast into HC3DP formwork. © Matthias Leschok, DBT.

5. A series of design explorations conducted by the MAS DFAB students 2023. Filament-based HC extrusion with a diameter of 10mm. © Fen Chan, DBT.

architectural scale offers a provocation to actual practice. Therefore, a radical position is presented where the necessity for discrete fabrication is celebrated through differentiated articulation of building elements according to their role and position in the constructive system (Fig. 2).

Large-scale ME offers the opportunity for geometric freedom and high articulation. However, it is better employed for the production of vertical elements, due to the anisotropic behaviour of the layer-based material deposition. The process of ME is scaled up with larger toolheads and extruding thicker and heavier beads (Duty *et al.*, 2017). Investigating methods to upscale ME with lower material intensity and higher volume output is necessary. Elements of architectural size need to be fabricated within hours, not days or weeks. HC3DP at large dimensions, introduced by Leschok *et al.* (2023), overcomes those problems by fundamentally changing the way large elements are 3D printed. With the introduction of HC3DP, the extrusion rate of thin-walled hollow-tubular polymer beads can compete with those of concrete 3D printing, while only using a fraction of the material.

On the other hand, for horizontal elements such as slabs and roofs, SFs present a more efficient system due to their three-dimensional action. Previous research has shown the benefits of 3DP joints for non-standard SFs, including minimising production waste and employing lower-energy-consuming materials (Kladeftira *et al.*, 2022). However, the fabrication of non-standard structures in-situ requires the assembly of individual elements at great heights and heavy machinery. Often, support structures are as dense as the structure itself. In this project the elimination of support structures was studied in combination with a customised modularisation strategy enabled by 3DP joints, allowing for efficient, safe, and fast assembly by humans without heavy or special equipment. Extensive research on connection principles and detailing between modules was performed as well as patterning and sequencing strategies that allow for gradual loading of the structure throughout the assembly process.

Constructive system and digital workflow

The pavilion is conceived as a modular aggregation of three long-spanning mushroom columns. It is composed of a 3D-printed column and a radial SF (Fig. 3). The columns are manufactured with HC3DP with a single outline, while the core of the column is hollow to accommodate post-tensioning cables and light sources that produce the final illuminating effect. The SF roof features a unique topology enabled by novel typologies


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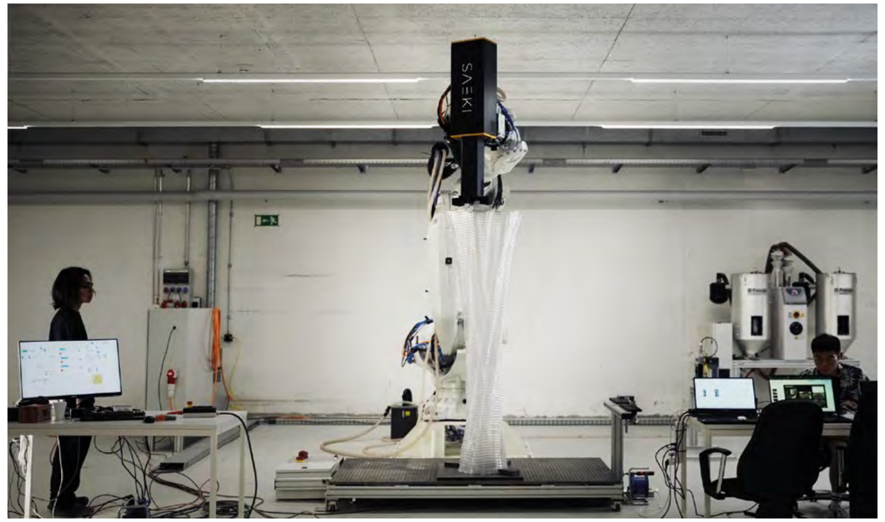

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of 3DP interlocking connections. The roof interlocks with the hollow columns with an intermediate component. The geometry of this SF module is adapted for each bespoke column such that it interlocks with the column's undulating geometry in the upper 25 layers. A post-tensioning cable runs through the central joint of the intermediate module, traverses the column, and is anchored to the concrete footings on which the columns are placed. The footings are shaped in continuity with the column geometry and HC3DP formwork is used to match the scale and resolution of the layered-base materiality of the column shaft (Fig. 4).

Each column–roof pair is designed and fabricated through a computational parametric workflow. Each 'mushroom' reacts to its relative position in the structure and the desired pavilion outline. The parameters for column design include fabrication constraints, such as continuous toolpaths, maximum overhangs, and minimum feature size. The designed undulations augment the stiffness of the 3DP elements in addition to the insertion interface for the SF. The design tool for the joints calculates the minimum joint volume needed to connect the tubes and orients the necessary connection details in order to create unique hybrid-detail connections tailored to their specific position in the structure.

Fabrication setup

To fabricate the pavilion, multiple complementary digital fabrication techniques are used. The columns and concrete formwork are HC3DP using a pellet extruder mounted on a 6-axis ABB 6700. The nodes are 3DP in PA12, with a 48MPa characteristic tensile strength, using the MultiJetFusion technology, a powder-bed process ensuring isotropic behaviour and high accuracy. The linear members employed for the SF are industrial 20mm glassfibre polymer rods. The bespoke-length tubes are cut in a human–robot collaborative setup, in which the human loads the feedstock and the robot slides the tube into the corresponding position for the cut to be executed with a stationary bandsaw. Pneumatic grippers are employed to temporarily lock the tubes' position during this process.

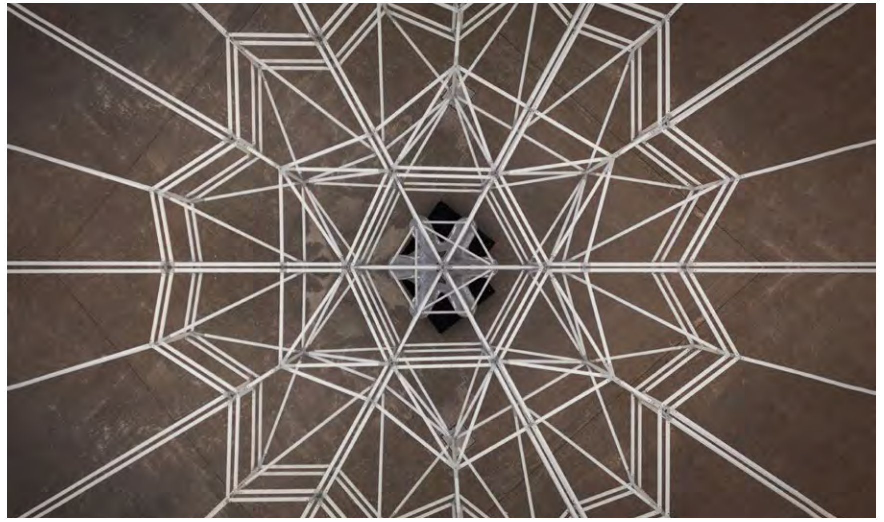
Creating lightweight architecture

In HC3DP, polymer feedstock is used to 3DP large-scale hollow-tubular beads (strands) instead of full cross-sections. This novel approach has many advantages compared to off-the-shelf large-scale 3DP methods, such as high printing speed, through improved cooling rate, reduced material consumption, and enhanced transparency. HC3DP pushes polymer 3D printing into an architecturally relevant scale, as the printing layer ranges from 10 to 24mm, while the build-up rate is comparable to concrete 3D printing (Anton, 2020). High-performance parts can be printed with a wall thickness of 1.0-2.0mm because of the higher strength-to-weight ratio tubular sections display, saving more than 85% of material compared with conventional AM.

PETG was used for the HC3DP of the columns, a co-polyester derived from the commoditised PET polymer, modified to improve its printability and featuring high transparency. Design explorations with robotic filament-based HC3DP were performed to investigate material and process limitations. An off-the-shelf extrusion system was adapted to use the HC3DP technology with a resolution of 10mm. The new aesthetics enabled through low-resolution, highly transparent polymer 3DP were explored in small-scale prototypes. This new printing technology allows for the creation of elements with extreme overhangs, woven structures, and non-planar 3DP. Elements of medium size were printed to understand manufacturing constraints and design possibilities, as shown in Fig. 5

6. Close-up of HC3DP process. Diameter of extrusion 24mm. © Girts Apskalns.

7. All columns were 3D printed at the fabrication hall of SAEKI Robotics, using one ABB IRB 6700 industrial robot. © Girts Apskalns.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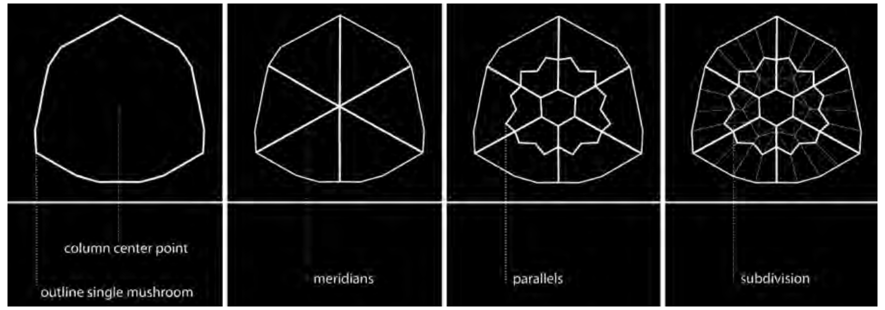

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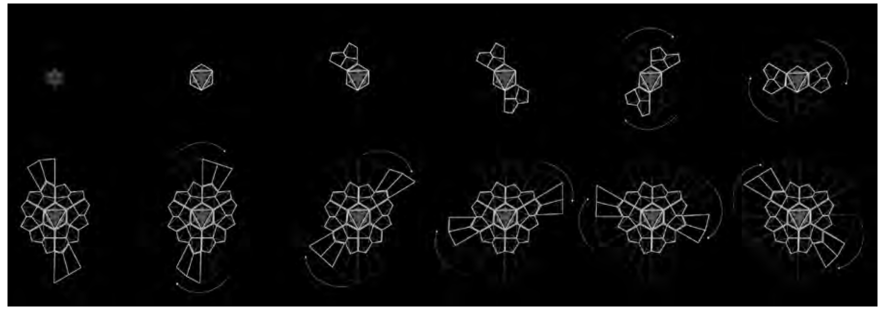
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8. Top view of one mushroom column. © Marirena Kladeftira, DBT.

9. Computational design framework. © Matthias Leschok, DBT.

10. Assembly sequence. © Nik Eftekhar, DBT.

Over the last two years a robotic end-effector was developed specifically for HC3DP enabling the 3DP of large-scale tubular beads, thereby improving the extrusion rate dramatically. The process was then adapted for the commercial pellet-extrusion system of SAEKI Robotics (Fig. 5). The tubular geometry of the beads is materialised with a bespoke nozzle and positive air pressure. The nozzle splits the molten pellet feedstock into a thin-walled bead and an empty core. Compressed air is injected into the hollow bead to create positive air pressure and prevents the bead from collapsing. For the final design of the columns, a nozzle design with internal bracing was used. The core is reinforced with a 'X' cross instead of an 'O' section. This was necessary to increase the stiffness of the elements and achieve higher loading capacity.

A diameter of 24mm and a layer height of 19mm was used in the project (Fig. 6). The extrusion rate is 7250mm^3/s (1308 material, 5942 air), rendering the 3DP of the 2.2m-tall columns in only four to six hours and with a weight of 10kg each for the 'O' section and 18-20kg for the 'X' section. A column with a comparable volume, printed with regular ME (6mm width, 3mm layer height, two outlines, one of them zigzagging), results in a ten-fold longer print time and four to five times higher material consumption.

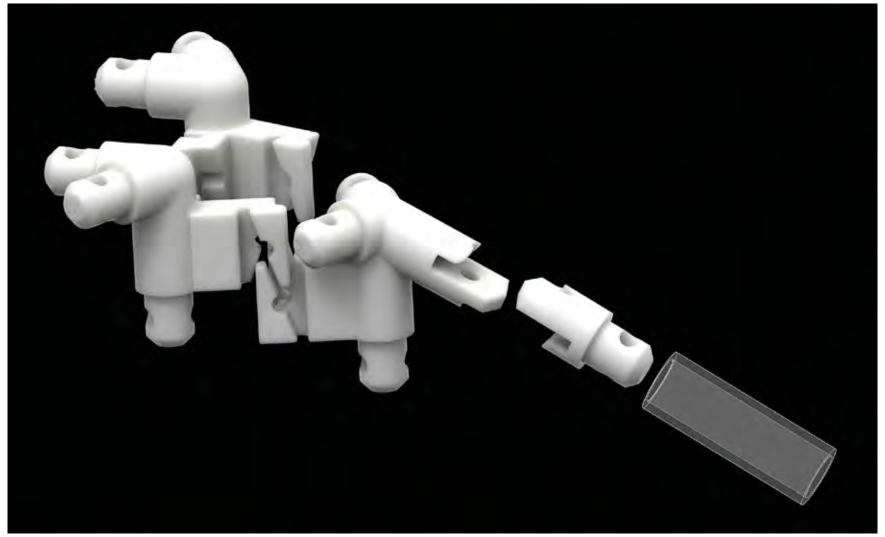
3DP enabled support-free assembly of modular SFs

The design of the roof is governed by three principles: modularity, support-free assembly, and disassembly through dry self-interlocking connections. The unique constellation of the structure and its non-standard layout require a custom SF enabled by 3DP joints light enough to be supported by the columns and stiff enough to span the 5.5m distance between them, as well as the 3m horizontal overhang (Fig. 8).

The roof is first discretised into three segments, designating the portion of the roof that is supported by each column. Subsequently, each segment is discretised further into modules according to the following principles: a radial array of primary beams ('meridians') is formed, stemming from each column outwards to the exterior ring of the SF. Perpendicular to the radial lines, parallel concentric polygons are formed through a subdivision schema ('parallels'). This two-way hierarchical grid and its density defines the amount and number of modules and signifies the axes along which doubling of members will occur. Each module is further subdivided in three-dimensional space, adding diagonals for rigidity and stability during assembly (Fig. 9).

Three typologies of joints were developed. Their geometry is a hollow shell with a seamless connection to the tubes and a 3mm wall thickness which, after mechanical testing, was fine-tuned to match the ultimate tensile strength of the plastic tubes. Two types of intra-module joints feature: a) a socket pin connection for the members of the boundary frame that are assembled first, and b) an intermediate piece for stiffening diagonals first attached via a socket connection to the tube and later fastened on the joint with a self-guiding slit and an interlocking pin. Finally, the module–module connections are formed via added self-interlocking details on the shells of the joints positioned at the interfaces of adjacent modules. They consist of a male–female self-guiding interlocking fork that allows for vertical insertion of the introduced module (Fig. 11).

The assembly follows a semi-circular sequence dictating the position of male/female details (Figs. 10, 12). First the intermediate module is inserted for connection to the column, and subsequently two cross-facing modules of the first parallel are placed to balance the weight. The size and weight of the modules are tailored such that they can be handled by one human, featuring an average weight of 3.7kg. Two people start adding modules radially until the full circle is assembled. Due to the segmentation scheme, all column–roof pairs can be fabricated in parallel with no expertise by crowdsourcing the assembly.



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Exhibition

The pavilion is exhibited in an industrial underground setting at Halter AG in Switzerland. The pavilion is exhibited surrounded by suspended HC3DP chandeliers (Figs. 13, 14, 15). No other light sources except for the ones installed inside the HC3DP elements are present in the room, contributing to the installation's dramatic impact.

A plastic future?

Prōtóplasto opens up a dialogue about the controversial use of plastics in architecture along with design-for-disassembly methodologies. It revisits the ideals for lightweight plastic architecture and proposes a new perspective on how to use circularly synthetic materials that can be reused or recycled multiple times during their life cycle. The combination of techniques and materials is an experimental search for more efficient use of materials and systems that leverage digital fabrication technologies and innovate equally in the microscale (material system) and the macroscale (construction system), as is evident from the extremely light weight of the structure at 3.8kg/m².

HC3DP provides further ground for experimentation at the architectural scale in building envelopes, formwork creation, ephemeral architectures, and product design such as bespoke lighting. Furthermore, the validation of modular support-free assembly with tailored connection details can provide a basis for future research founded on the same principles as aerial automated assembly by flying machines and collaborative human–drone construction, thanks to the ultra-light character of the modules and self-interlocking details.

11. Module–module connection to support-free assembly. © Marirena Kladeftira, DBT.

12. Support-free assembly, last element being placed. © Girts Apskalns.

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13. Installation view showing the 2.2m-tall HC3DP chandeliers surrounding the pavilion display. © Girts Apskalns.

14. One of the 2.2m-tall HC3DP chandeliers suspended from the ceiling to frame the exhibition. © Girts Apskalns.

15. A series of 2.2m-tall HC3DP elements aligned and alight. © Nijat Mahamaliyev.

Acknowledgements

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UPSCALING MYCELIUM-BASED COMPOSITES
STRATEGIES FOR BIOFABRICATION OF SUSTAINABLE BUILDING COMPONENTS

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Mycelium composites: Potentials and limitations

As one of the largest CO2-emitting industries, construction is still far from being sustainable. Adopting circular design strategies and aiming at achieving net-zero or carbon-negative performance on building materials are crucial steps towards a progressively environmentally friendly construction industry. The key strategies for this challenge focus on reducing waste generation and maximising the service life of the components. One solution, therefore, could be to increase the use of fully bio-based building materials and reduce the amount of CO2 emitted during and after the building process. In recent years, research on mycelium-based composites (MBCs) has demonstrated their significant potential to replace a variety of construction materials as a sustainable and renewable alternative. However, with few relevant exceptions, there remains a lack of established methods to produce large-scale MBC components, due to both the low structural capabilities of such composites and technological and design limitations.

Most precedents exploring the use of MBCs in an architectural context, apart from furniture applications, can be categorised into two types: discrete elements construction and monolithic construction. Discrete elements-based mycelium structures have been proposed for a decade and are still the most common strategy to achieve larger designs, relying on the combination of smaller elements such as bricks, panels, and others. Applications like acoustic panels from MOGU (Mogu Srl., 2022), cladding systems like the Tropical Town Project Batam, Indonesia (Tropical Town Project Batam, 2019), the Growing Pavilion in the Dutch Design Week in 2019 (Leboucq *et al.*, 2019), or acoustic sails such as the Myx Sail (Dwan *et al.*, 2023), while demonstrating the production of effective acoustic elements and sustainable construction material alternatives, are nevertheless composed of elements of a relatively small size, which are used mostly as cladding for an existing structure. Larger designs employing discrete elements, such as the Hy-Fi Tower (Stott, 2014) and MycoTree (Heisel *et al.*, 2017), also rely partially on supporting structures or use the MBC material mainly in compression. Monolithic structures, such as the El Monolito Micelio (Dessi-Olive, 2019) or the BioKnit pavilion (Kaiser *et al.*, 2023), are structures that are either grown directly on site or in a growing chamber in a single piece. These take a step further in making large MBCs, but often rely on large scaffolding or internal reinforcements and hence do not take advantage of

mycelium's inherent properties. Within these two extremes, this paper identifies existing limitations for the integration of large-scale MBCs in the architecture and construction industry, proposing strategies to overcome them and increase the applicability of MBCs as architectural materials.

Upscaling strategies for mycelium composites

In order to expand the range of applicability of MBCs as sustainable construction materials, this paper presents a series of strategies for the design and fabrication of full-scale non-structural partition walls. The goal is to envision processes to efficiently produce fully bio-based, CO_2-neutral, circular building components for interior office spaces (Fig. 2). In this context, non-structural partition walls have been identified as some of the building components with the shortest lifespans, often relying on the use of synthetic composite materials that are difficult to reuse or recycle (Rossi *et al.*, 2022). These elements usually consist of panels with a height of 3–4m and 1m width, and a total wall thickness of around 10–12cm. The structural requirements of standard partition walls cannot be met with MBCs in those dimensions; hence, they require novel strategies for their upscaling to such scale.

Of the many possible strategies, two have been identified as most promising. The first one relies on the integration of a bio-based reinforcement system, much akin to the way steel is added in reinforced concrete, to increase the tensional and bending resistance of MBC components. The second strategy relies instead on fragmentation of the element size into smaller components, which are compatible with the material properties of mycelium, to be produced using 3D-printed lost formworks made of bioplastics that allow the precision needed for their integration into an assembly system through kinematically interlocking interfaces.

These two strategies have been selected in relation to the shortcomings in both the production process and the resulting performance of MBCs; indeed, the first strategy aims at allowing the production of larger elements in a single piece. This is desirable for their application in construction, but it comes at the cost of requiring larger production facilities for sterilisation of the substrate, for its cultivation and stabilisation after growth, as well as larger and more costly moulds. On the contrary, the second strategy allows for a segmented production of smaller elements, requiring no mould and smaller production equipment for all stages, but results in components that are subdivided in smaller elements, a solution not always desirable for the production of partition walls.

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Rather than providing a unique solution, the proposed strategies aim at exploring the range of possibilities available for the development of partition walls using MBCs. In both cases, the goal is to allow the production of circular building components made exclusively from bio-based materials, which could be reused multiple times through their lifespan, and eventually composted without residue at their end-of-life.

Robotic additive manufacturing of veneer reinforcements for MBCs

Previous research has identified the fundamental limits to the application of MBCs for large-scale architectural components as lying in the poor tension and bending resistance of these materials. As such composites are produced by binding lignocellulosic particles through mycelial growth, the resulting products have varying degrees of compressive strength. This is mostly dependent

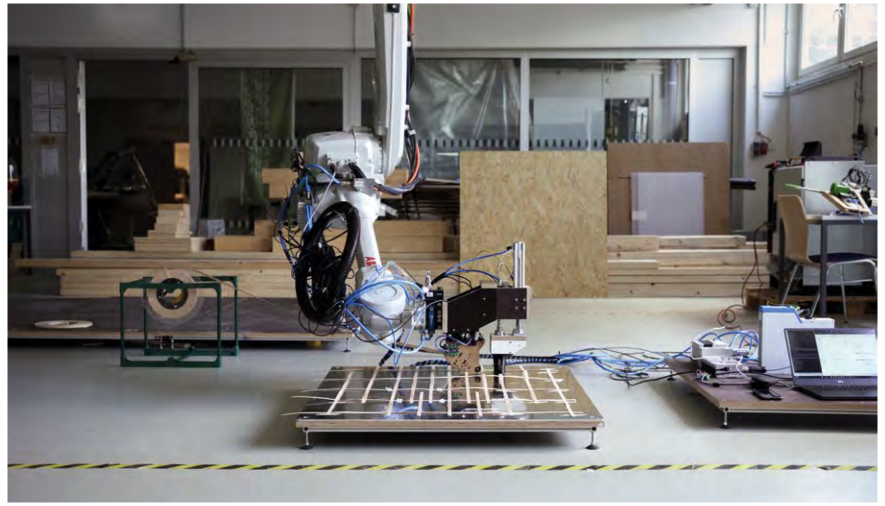
1. Detail of the interlocking between mycelium blocks grown in 3D-printed bioplastic formworks. © EDEK Uni Kassel, photo by N. Wefers.

2. Full-scale demonstrator for an MBC wall reinforced with a 3D wood veneer lattice. © EDEK Uni Kassel, photo by N. Wefers.

3. Robotic setup for the automated fabrication of 3D wood veneer reinforcement lattices. © EDEK Uni Kassel, photo by M. Schmidt.

4. Close-up of the robotic additive manufacturing process using continuous wood veneer strips. © EDEK Uni Kassel, photo by M. Schmidt.

5. Close-up of the ultrasonic welding process for the glueless binding of veneer. © EDEK Uni Kassel, photo by M. Schmidt.



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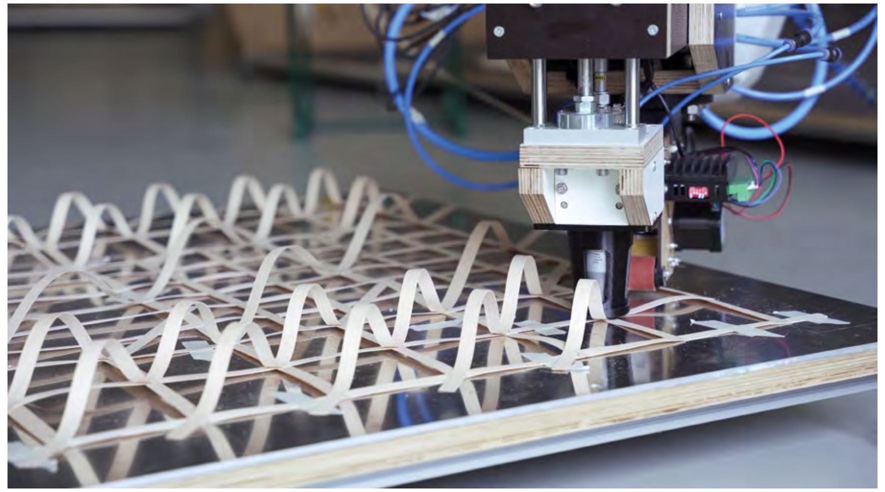

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on the nature and size of the particles used, but the low tensile strength is largely due to the lack of longitudinal elements that can transfer tensile loads across the component; hence only having mycelium to hold the particles together.

In response to this, additively manufactured three-dimensional wood lattices were integrated within the MBC matrix to increase the structural capacity of the composite. These lattices, manufactured from thin edge-banding rolls of maple wood veneer, introduce long fibres to the composite and can be oriented according to the expected stresses in the geometry. These act both as reinforcement, like traditional high-performance composite materials such as steel-reinforced concrete, and as natural scaffolding for mycelium growth, during which the mycelial network can bind to the veneer and realise a novel reinforced composite. Although previous research identified a relatively weak bond between veneer and mycelium (Özdemir *et al.*, 2022), the kinematic jamming of the veneer grid within the substrate particles allows the veneer to effectively work as a tension element within the matrix. As demonstrated through structural testing, the introduction of a three-dimensional veneer lattice significantly increases the elastic modulus and hence the strength of the resulting MBC. Such novel composites therefore provide the necessary strength to produce large-scale thin partition walls, enabling MBCs to span greater distances and withstand the loads associated with their use in building elements.

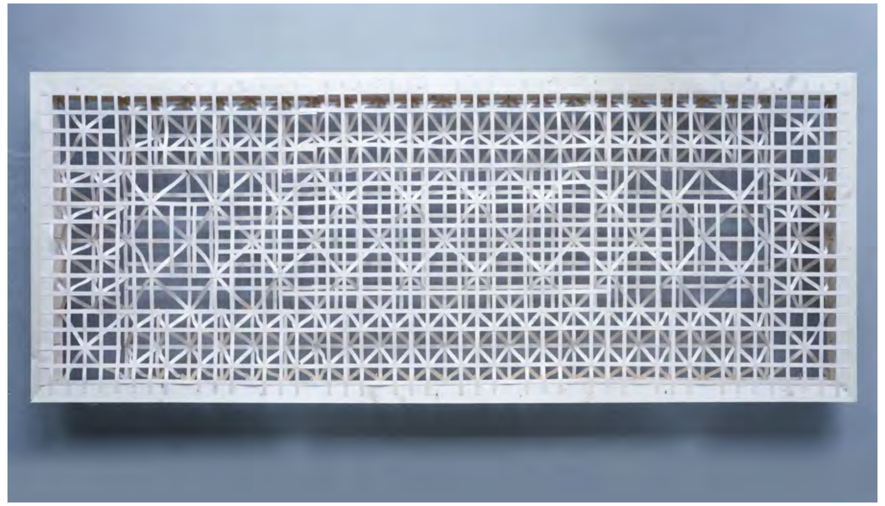
In order to adapt the reinforcement lattice designs to the unique needs of each component, an automated robotic additive manufacturing process to produce 3D veneer grids with custom layouts was developed (Fig. 3). The process, relying on a 6-axis industrial robot arm and a specifically developed end-effector, allows it to extrude the veneer strip in selected locations, cut it, and bind it to already placed strips (Fig. 4). Through a computational design interface, digital lattice designs can be converted into instructions for the robot arm, making the production of lattices possible with a maximum extension of 1m and thicknesses varying up to 15cm.

A key challenge during the development was the identification of a bio-based binding method that would be compatible with the process speed. Most bio-based binders either require long curing times or rely on coating the veneer entirely with the binder, a process that would negatively influence the veneer–mycelium bond strength. Hence, it was decided to avoid using any binder, and to rely on an ultrasonic welding process. This process, usually applied to the welding of thermoplastics

(Troughton, 2009), utilises a titanium horn that vibrates at ultrasonic frequencies while being pressed on the material. The kinetic energy is then transformed into thermal energy, effectively melting and welding the material. While the possibility of using friction welding, a similar method to ultrasonic welding, to weld large wood elements through an industrial press, has been demonstrated before (Hahn, 2014), thanks to the minimal thickness of the veneer, a small horn and a pneumatic piston mounted on the end-effector were sufficient to activate the welding process (Fig. 5). When pressed on the veneer strip, the vibration energy melts the lignin naturally present in the wood, which, upon hardening, binds two pieces of veneer strip together in a fraction of a second. Tensile testing demonstrated that such a connection has higher strength than that of the veneer itself (Özdemir *et al.*, 2022), therefore proving to be a suitable method for the production of veneer lattices. This robotic production method allowed the automated fabrication of a full-scale reinforcement grid of 2.40m height and 0.8m width with a thickness of 10cm, produced in three separated parts, and then manually bound into a single grid (Fig. 6).

Additionally, the lattice production method allowed the production of curved reinforcement geometries. By geometrically defining the distances between the veneer strips in the top and bottom layers of the panel, it was possible to control the resulting curvature of the final element, as differences between top and bottom layouts would cause the lattice to bend towards the side with shorter distances. As a result of the curvature of the panel, human intervention for the final welding between the top and bottom parts of the panel was needed.

The three-dimensional lattices produced through this automated process were then used for the cultivation of mycelium. Given the relatively weak bonding between the veneer and the mycelium matrix, the lattices were first spun within a timber frame, which ensured their functional behaviour as tensile elements, while also providing mounting interfaces for the final panel. Such lattices could then be filled with hemp shives inoculated with *Ganoderma Lucidum* fungi (Fig. 7). During this process, it was possible to use moulds to add relief and texture to the panel's outer surface, achieve additional design freedom, and offer potential for acoustic performance tuning (Fig. 8). Within one to two weeks of cultivation in a controlled environment, the hemp matrix and the veneer lattice were bonded by biogrowth, creating a stable composite (Fig. 9). In this novel composite material, compression and buckling resistance is provided by the mycelium–hemp matrix, while the veneer improves the ability to withstand tensile and bending forces.



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After growth, the panels were dried for 24 hours in the growth chamber using infrared panels to heat the air, stop the mycelium growth, and remove most of the contained water. This significantly reduced the weight of the panel, while increasing its hardness. As a proof-of-concept, one of the produced panels was tested structurally with a basic setup, spanning the panel between two supports at 2.20m distance from each other. The panel sustained a load of 420kg, applied through sandbags placed onto the middle section, with a deflection of 16mm. This test demonstrated the feasibility of the proposed reinforcement approach to significantly increase the strength, and hence the range of applicability, of mycelium composites.

The method allowed the production of different prototype elements at a partition wall panel scale. Specifically, two panels were produced, both with a height of 2.40m and width of 0.80m and 0.92m, respectively. The first panel, which was produced to test the material feasibility using a manual welding process, presents a uniform reinforcement grid and a smooth outer surface (Fig. 10). The second panel includes a reinforcement grid customised to the expected stresses and was produced entirely using the proposed robotic additive manufacturing method. It has a designed surface relief to increase its acoustic scattering performance (Fig. 2). In addition to these flat panels, a smaller demonstrator was produced with a single-curvature reinforcement grid. This, combined with a thin plastic mould, enabled the production of precisely designed curved elements, demonstrating the method's feasibility beyond flat surfaces. As the prototype was produced for an exhibition, half of the reinforcement grid was left exposed for visitors to examine (Fig. 11).

6. Complete 240x80cm reinforcement lattice with the outer support frame. The lattice was robotically manufactured in three separate parts and assembled. © EDEK Uni Kassel, photo by M. Schmidt.

7 Filling process of mycelium-inoculated hemp substrate into the reinforcement lattice. © EDEK Uni Kassel, photo by M. Schmidt.

8. Close-up of the lower mould surface for the textured mycelium panel. © EDEK Uni Kassel, photo by M. Schmidt.

9. Detail of the binding between the mycelial mass and the wood veneer reinforcement lattice. © EDEK Uni Kassel, photo by N. Wefers.

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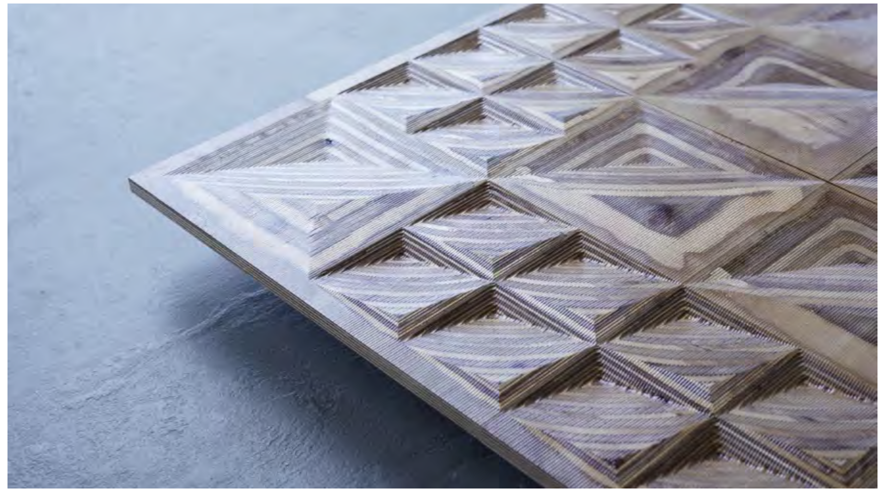

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Upscaling through fragmentation

In addition to veneer-reinforced panels, methods to design and fabricate block-based modular construction systems using MBCs have also been developed, with the aim of allowing large assemblies to sustain both compression and tension forces that are typical in architectural components. To this end, while also ensuring the reversibility of the final assembly, it was necessary to develop an assembly system based exclusively on friction-based interfaces, avoiding the need for gluing or the use of fasteners.

Topological interlocking assemblies (TIA) are a class of structural systems based on kinematically interlocking elements that can be assembled into structures supporting loads in multiple directions without binding agents (Estrin *et al.*, 2011). For this, they rely on the precision of the interlocking interfaces, which ensure correct transfer of loads through friction across the modules and their mechanical interlocking with the fixed outer boundary. This is achieved by arranging the blocks and their interfaces so that each one acts as support for, and is supported by, the neighbouring blocks (Tessmann and Rossi, 2019). While mycelium composites have been explored to create a variety of block-based structures, precision has been an issue due to the shrinkage and the non-uniform nature of such materials. This in turn required either the use of additional timber interfaces for fastening (Heisel *et al.*, 2017) or the reliance on interfacing methods that would work simply through stacking.

For this reason, a method was developed for the bio-fabrication of TIA systems, combining additive manufacturing with bio-based materials and mycelium cultivation, allowing the creation of larger assemblies able to sustain loads in multiple directions. This was achieved through Fused Deposition Modelling (FDM) additive manufacturing of an outer shell with polylactic acid (PLA) bioplastic infused with wood particles, to be used as a lost formwork for the cultivation of MBC. The presence of wood particles in the printed material ensured that the mycelium would penetrate through the printed shell by feeding on it, providing a strong bond between the two. Hence, the outer shell delivered the required precision to allow for the kinematic interlocking of the blocks, while the mycelium provided the infill and therefore ensured the stability of the block against compression forces (Fig. 1).

Despite the dimensional stability of the outer PLA shell, the strong bonding created with the mycelium infill resulted in considerable shrinkage during drying. In order to address this, the interlocking details' depth was tuned

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so that the detail would have sufficient depth for kinematic interlocking despite shrinkage. Furthermore, the drying process was adapted by placing the blocks on custom racks and rotating them regularly to avoid uneven shrinkage due to gravity.

The resulting system is composed of blocks held together exclusively through mechanical interlocking and fixed through an external compression frame made of timber. As no binder was used, removing the screws holding the timber frame allowed the panel to be disassembled into individual blocks, hence providing a fully reversible assembly process. The system was used to fabricate a full-scale partition wall prototype with a height of 2.40m, consisting of 112 interlocking blocks, produced with small-scale consumer 3D printers (Fig. 12). To demonstrate the potential for variability offered by the system, some of the elements were designed with different heights. While this was done exclusively for aesthetic purposes, it would be possible to tune such variation to achieve custom acoustic performance, or to include functional elements within the panel, such as shelves. It must be noted that the height variation does not affect the shape of the interlocking geometry, so that all blocks could still be used interchangeably to reconfigure the system for other purposes. Given that PLA bioplastics are compostable only through industrial composting, research is ongoing into replacing them with fully compostable alternatives such as wood-based or cellulose-based pastes. While this would increase the biodegradability of the elements at their end-of-life, it introduces further issues with accuracy, as both materials undergo significant shrinkage after printing. To address this, simulation tools might be used to predict the material deformation during drying and consider it in the design phase (Rossi *et al.*, 2023).

Conclusion

The presented strategies for expanding the range of applicability of MBCs as sustainable construction materials demonstrate the potential of such materials to produce interior partition elements at an architectural scale. The presented large-scale prototypes validate the feasibility of architectural-scale fabrication using MBCs and provide initial insights into the behaviour of large-scale MBC components. Further research is required to explore such potential in relation to customisation of the internal reinforcement lattices, the mycelium substrate properties, and the surface quality according to different application requirements.

Rather than striving for a single optimised production approach, the described strategies aim at presenting a wide catalogue of design solutions for MBC integration in architectural design, to produce fully bio-based components for applications in a circular design context. The size options, connection typologies, reinforcement strategies, and surface qualities aim at offering a wide range of solutions to be further explored and developed for specific architectural and design applications. Based on the presented initial prototypical studies, they show significant potential to design and fabricate sustainable, large-scale architectural elements using mycelium-based composites (Fig. 13).

10. Full-scale flat demonstrator for a wood-veneer-reinforced MBC partition element with uniform reinforcement grid. © EDEK Uni Kassel, photo by N. Wefers.

11. Single-curvature partition element. The upper part of the 3D lattice is left exposed as a demonstrator of the reinforcement process. © EDEK Uni Kassel, photo by N. Wefers.

12. Full-scale demonstrator of an MBC wall composed of topologically interlocking blocks. The blocks are held together exclusively by the frame, so removing it allows fully reversible disassembly of the wall and reuse of the blocks. © EDEK Uni Kassel, photo by N. Wefers.

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13. Close-up of the textured surface on the final full-scale demonstrator. © EDEK Uni Kassel, photo by N. Wefers.

Acknowledgements

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MATERIAL VERSATILITY, LOCALITY AND CHANGE IN CIRCULAR DESIGN

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Introduction

The discipline and practice of architecture is facing a profound dilemma. The pressure on planetary boundaries requires the rethinking of architecture's reliance on CO2-rich materials and energy-intensive processing. At present, calls envisioning a sustainable building culture focus on renewable and bio-based materials as solutions for carbon neutrality. However, many of these practices carry over industrial paradigms of mass production and standardisation, creating a fundamental reliance on virgin materials and an inability to achieve true cascading. Instead, they intensify the pressure on the ecologies from which materials are cultivated and harvested.

This paper asks how the ideation and prototyping of waste-sourced bio-based materials can drive new models of circularity and reuse in architecture. With a special focus on 3D-printed biopolymer composites, the paper describes the creation of a versatile material system that can respond to local resource availability. Here, the additive logic of 3D printing is extended to support models of functional material grading that can combine variations of the material recipe to create complex composite architectural panels – first, through strategies of material pleating, and second, through in-process grading.

The paper asks how circularity can challenge models of resource deployment in architecture, and how they might expand the axioms of digital design and fabrication from being driven by models of performance optimisation to incorporating new sensitivities to resource locality.

Local sourcing and variability in the design space
Renewable bio-based resources are categorised as being either first-generation, including food crops and plants; second-generation, including non-edible lignocellulosic biomass or by-products from first-generation production; or third-generation, including algae and food wastes (Bardhan *et al.*, 2015). In the region of southern Scandinavia, where this research is being developed, the landscape is predominantly agricultural. Over centuries it has been optimised to produce high-value biomass focused on food and fuel in the categories of grains, fodder crops, and timber. As a result, the landscape is fully productive and first-generation resources are wholly incorporated into existing material flows. However, the same landscapes and cultivation

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practices generate second-generation biomass resources that are not fully utilised. These include wastes and residues including the cut-offs and unused parts of first-generation materials, which are burnt, landfilled or composted, or left to decompose. In general, these biomass resources are seasonally dependent and connected to local agricultural practice and *terroir* (Lucini *et al.*, 2020). Their properties and quantities vary in line with the distinct local environmental and ecological attributes such as soil conditions, micro-environments, and practices of soil conservation. Furthermore, they are sensitive to climatic dynamics including drought, flooding, and disease. Alongside these material streams emerging from cultivated biomass, third-generation uncultivated biomass such as beach-cast seagrass, at present an abundant seasonal resource, can be gathered from coastlines and fjords. As with the first- and second-generation resources described above, the quantity and quality of these third-generation materials are impacted by their local environment and are not consistent.

Beyond this agricultural landscape, anthropogenic wastes such as cotton from linens and clothing are another source for bio-based materials. These materials are sourced through recycling loops. Often the properties of these materials are standardised as a result of industrial processing. However, as they are collected for waste they co-mingle, and the properties of this standardisation need to be carefully sorted in order to be preserved. While this may be possible for certain material streams, it is not feasible for most, making this material resource inherently variable.

First, second, and third-generation materials are part of the circular bio-economy and as such are subject to the same supply and demand dynamics as other resources. At the moment, the circular bio-economy is on a trajectory of rapid development as many industries seek to transfer their production to renewables (Kircher, 2022). This puts additional pressure on the architectural pathways for valourisation of bio-based materials. As new resource loops emerge, previously undervalued materials escalate in value and scarcity. As such, the idealisation of renewables as abundant is ruptured. Instead, we arrive at a resource sensitivity characterised by environmental and ecological dependencies, extreme variability, and changing availability.

These dynamics of resource availability call for new models of material specification and production (Ramsgaard Thomsen and Tamke, 2022) that do not assume the abundance and ready availability of standardised materials, and instead address two co-dependent criteria: *material variability* – the ability to interchange material constituents in response to local availability – and *material optimisation*, the ability to specify materials in response to design or performance criteria.

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1. The design composition is generated computationally using a natural growth algorithm called Space Colonization. This algorithm mimics the way that trees and other plants grow in nature, by simulating the growth of branches from a central trunk.

2. *Radicant* is a 3D-printed biopolymer composite interior wall panelling system installed in the Aedes Gallery, Berlin, in 2022. The 26 panels vary in their material composition and are composed of interlacing print beads and differentiated material recipes.

3. *Biopolymer Graded Panels* prototypes an exterior weather screen to assess the opportunities for exterior application of the biopolymer composite, and to monitor the response of different versions of this material to variations in environmental heat and humidity.

A case for designing with resource sensitivity

In our work we explore these resource sensitivities through the case of 3D-printed biopolymer composites. These are explored through the creation of architectural panels for interior and exterior use investigated through two different experiments. In the *Radicant* demonstrator we examine the architectural panel as a retrofitted interior cladding, while in *Biopolymer Graded Panels* we prototype the creation of an exterior weather screen.

In both cases, the panels are developed as deep reliefs with varying material compositions. The panels are 3D printed on a flatbed and the relief is built up through varying layer heights. The print patterns are designed to accelerate the post-printing curing process. The lace-like patterns produce a high surface to volume ratio, creating a large evaporation surface by which the material can release water content.

Both biopolymer experiments are based on a collagen binder mixed with cellulosic fibres that act as both reinforcements and fillers. Both collagen and fibres are residues of food and agricultural processes. The collagen is bovine, extracted from the meat industry, while the cellulose fibres are derived from various waste streams endemic to our local context. These are bark and wood flour originating from the timber industry, cotton sourced from clothing recycling, and seagrass, a source of blue biomass finding new applications in isolation and packaging.

The collagen biopolymer can become thermoplastic when plasticised with water and polyols (Nicholas *et al.*, 2023a). To achieve a fluid printable state, the material is heated and then mixed. During the 3D-printing process, the temperature of the material is controlled, allowing us precise temperatures at the extrusion head and immediate cooling around the nozzle. This is done through the making of bespoke robotic extrusion heads combining heating and cooling processes. As part of the fabrication process, the material system undergoes a post-printing state change as it first cools, then cures. As water evaporates during the curing process, the material hardens, becoming resilient and stiff.

The material system is understood as a variable recipe space, which can be adjusted in response to material availability and locality. By mapping multiple recipes against their performance, we challenge the idea of material tuning as the search for a single optimum, instead creating a solution space that can be navigated in response to resource locality and availability providing multiple optima for defined performance criteria. The recipe space can be repeatedly extended and altered, adding new cellulose sources as locality and availability change.

For our studies, the building of the recipe space is based on material testing of strategic recipes spread out across the recipe domain. The tests characterise the strength ratios and elastic modulus of the recipes and allow us to compare the performance of the recipes. The recipes are understood as occupying a dimension mixing different degrees of binder, fibre, and filler sources. The manipulation of the balances within the recipes has direct impact on the resulting material performance. In this way we engage with processes of functional grading enabling the tuning of material composition in response to design-driven performance criteria.

Two approaches for material grading in a variable recipe space

The breadth of the recipe space is used actively in the design of the architectural panels. In the two experiments we create differentiated multi-material print strategies that allow us to deploy varying materials and grade performance. The two strategies are understood as extensions of each other that can be combined, *Radicant* by strategically pleating the different recipes together in multi-material assemblies, and *Biopolymer Graded Panel* by grading the recipes using a multi-extruder 3D printing head enabling a seamless transition between the recipes. Both strategies are developed by creating an extended digital chain that defines the geometry, details the print path, and steers the material specification of each panel.

Radicant: Pleating multi-material composites

In *Radicant* the panels are composed of multiple recipes that are interwoven – or *pleated* together – through a layered design. Pleating the materials results in complex composites that combine different instances of the recipe.

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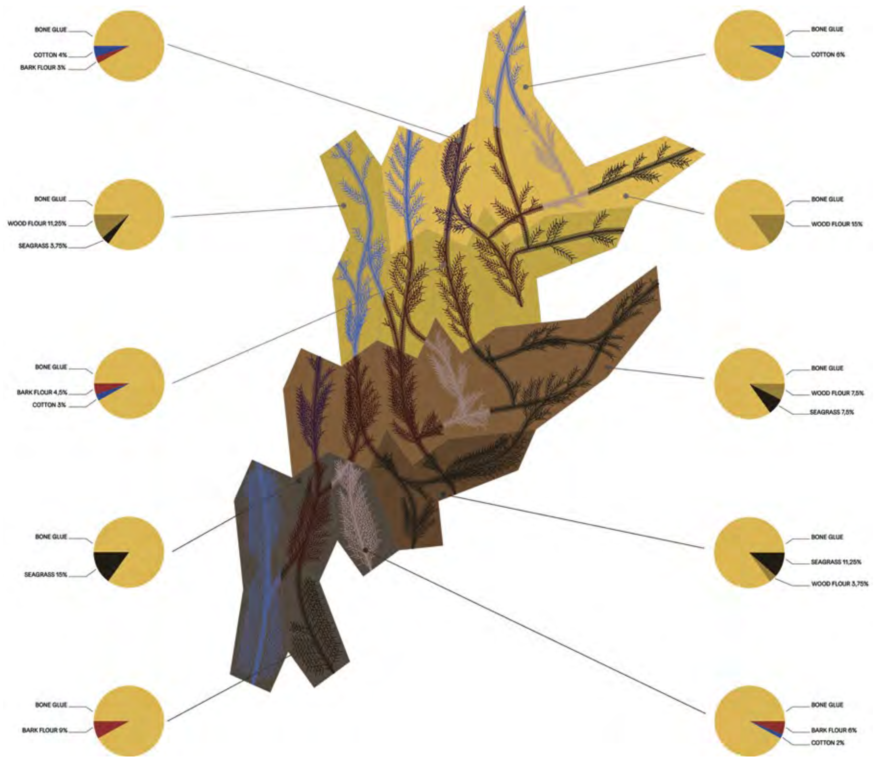
4. Dog bone samples of differentiated material recipes containing cotton, bark, wood flour, and seagrass fillers. Different fillers impact the mechanical properties of the material. By thinking exploratively rather than towards single-recipe optimisation, we utilise the breadth of this recipe space.



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5. In *Radicant*, the material specifications for each panel respond to the geometry and structural considerations of the design while also incorporating aesthetic considerations. The choice of material, together with the toolpath density, dictates the structural performance stiffness, weight, and visual expression of each panel.

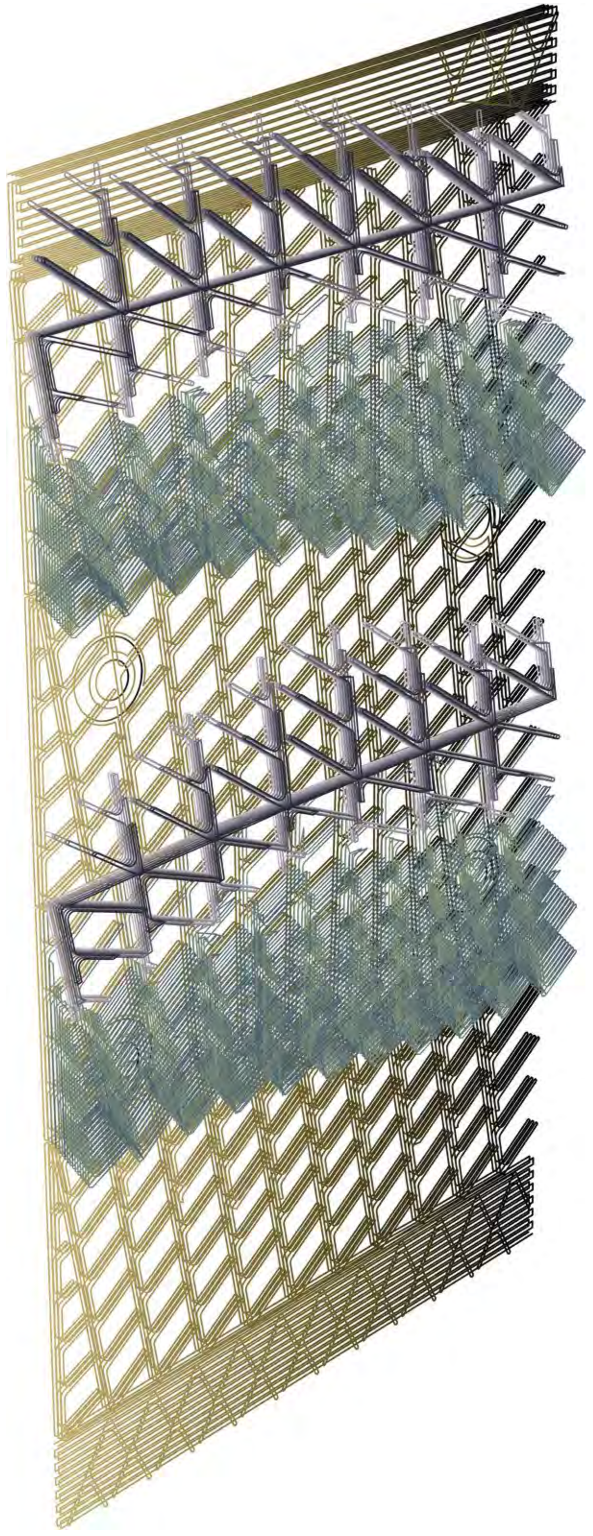
The pleating strategy follows a geometric approach (Nicholas *et al.*, 2023b) and is based on a sequential printing logic. The panel structure is built up in strategic layers that organise the print paths both layer-by-layer and material-by-material, taking into consideration fabrication restraints such as path collision, nozzle spacing, and robot arm placement. The pleating strategy is built up as a structural hierarchy in which base filler layers are followed by a 'trunk structure' and a set of 'branches' that bring an overall assembly-level continuity to the structure.

The 24 panels in *Radicant* are composed of a total of ten different recipes. These combine the base binder mix, comprising collagen, water, and glycerine, with variant proportions of cellulose sources including bark flower, wood flower, seagrass, and cotton. The choice of fibres affects not only the structural properties of the mix, but also its texture, colour, and finish. For example, glue matrix mixed with 30% wood flour produces a material with 0.7g/cm^3 density, 1.35GPa Young's modulus, and a yellow sandy finish, whereas mixing the glue matrix with 30% cotton results in a satin blue material with 3.15GPa Young's modulus, and 1.1g/cm^3 density.

The *Radicant* panels are printed using a robotically steered 3D extrusion process deploying pressure to steer the extrusion. The premixed materials are prepared in extrusion containers that are replaced during the printing process. The heated material achieves the correct viscosity for extrusion at 60°C and integrated heat pads maintain constant print process temperature. The recipe variation affects the rheology of the biopolymer composite. By varying the air pressure, these material changes can be accommodated.

Biopolymer Graded Panels

In *Biopolymer Graded Panels*, we realise continuous grading strategies that seamlessly transition between different recipes of varying viscosity and expression. The specification of grading is achieved through definition of changeover points, where one material flow is enabled and the other is reduced. The grading occurs over the distance of the toolpath, which therefore plays an important role in the legibility and speed of the material transition. *Biopolymer Graded Panels* tests three different grading strategies. In the first, a checkerboard pattern is applied to the panel base in four sections. This strategy maximises the time a material is printed before the switch of material occurs. The second grading strategy splits the base in similar-sized sections. However, instead of alternating the same two material distributions, one of the materials becomes gradually more blended to create a



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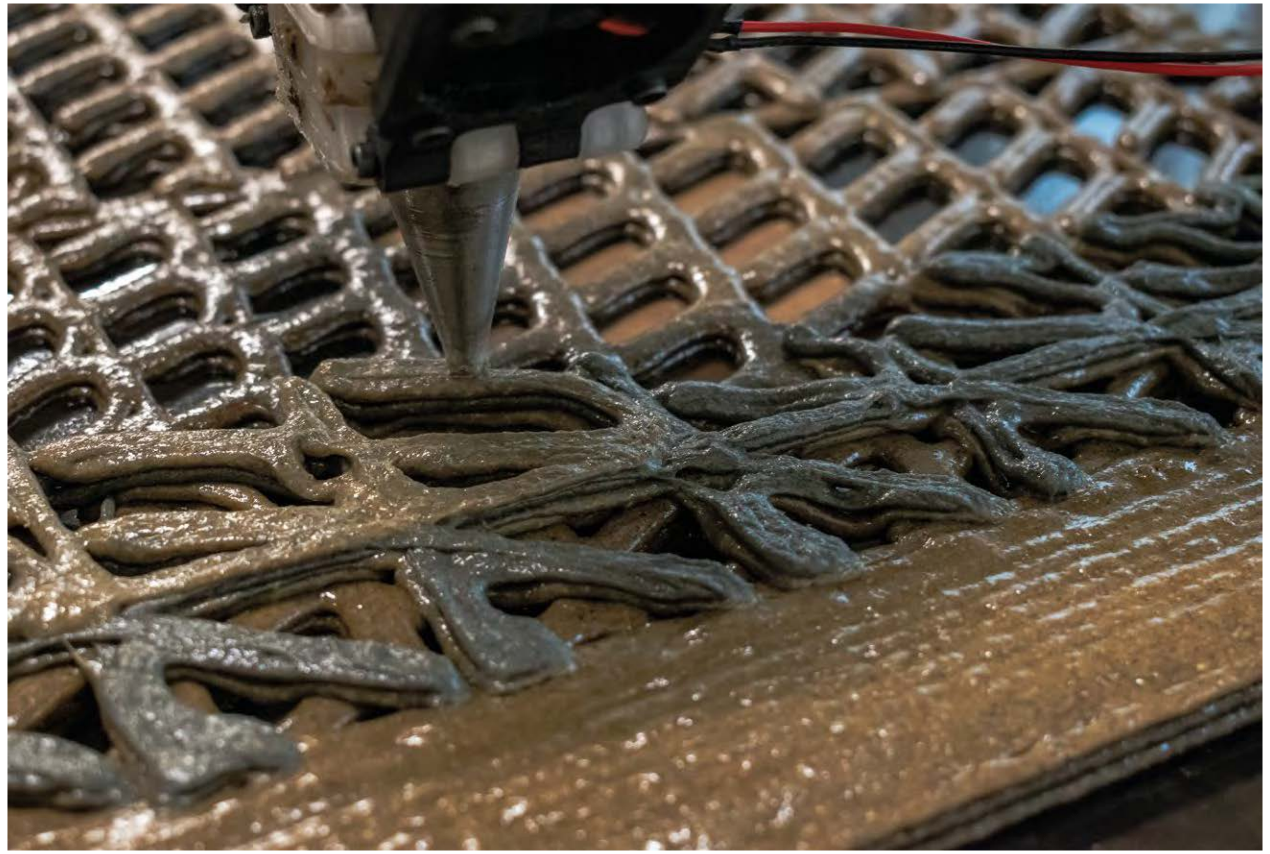
6. In *Biopolymer Graded Panels* the print geometries and material specifications are varied in response to design features, including overhangs, density changes, and connection points, as well as panel-scale grading strategies.



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gradient that transverses the entire panel. In the third strategy, the grading scheme incrementally increases the time spent printing with each material, creating a single longitudinal gradient throughout the entire panel.

The panels are printed using three recipes. The first is cotton-based, contains 6% cotton fibres by weight, and exhibits a distinctive blue hue. A second material blends 6% bark fibre and 3% cotton fibre to the base biopolymer. The third recipe is wood flour based, and blends 10% wood flour with 1% cotton fibre. In this material, the larger-sized grains are clearly visible.

A custom multiple-feed extruder and feeding system was developed to realise these continuous grading strategies. The design of this system incorporates key considerations regarding material viscosity, temperature control, the mixing of multiple material feeds, the implementation of continuous feeding from a separated reservoir, and the grading control in the fabrication code. The nozzle accepts feeds from two separate pneumatically controlled material feeding reservoirs. Each external reservoir can hold 3l and can be refilled or replaced during the printing process without introducing inconsistencies or artefacts into the material flow. The extruder is able to grade from one material to another within 3m using a 4mm nozzle.

Conclusion

In this paper we address the potential for bio-based materials to drive new models of circularity and reuse in architecture. If the use of bio-based resources as construction materials is to be intensified as part of a sustainable building culture, there is a need to diversify the materials used, and to localise their sourcing. Where virgin and first-generation materials are already fully utilised in regions such as ours, new design and fabrication pathways for second and third-generation-based biomaterials need to be created. To be flexible, these should be grounded in an appreciation of the locality and accessibility of resources, as well as the variability of quantity and quality that is inherent to second and third-generation biomass. These considerations present a new dynamic in resource flow that challenges modern assumptions of abundant and standardised materials.

7 & 8. Detailed view of the grading achieved during the printing process. The density of toolpath geometries plays an important role in the legibility of the material transition, with grading occurring more quickly in areas of high density.

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We have grounded our exploration in two cases that demonstrate interior and exterior applications for 3D-printed biopolymer composite panels. The biopolymer composite is developed to be flexible to the changing availability of waste streams and supports a variable recipe space through the ability to vary and interchange constituent materials. The *Radicant* and *Biopolymer Graded Panels* cases demonstrate how this is operationalised through printing strategies, specifically pleating and continuous grading, which tune the material composition in response to design-driven performance criteria.

The projects ask how architecture can expand its methodologies to incorporate fresh ideas of the grown and the harvested. It questions the axiom of abundance, instead presenting new methods that extend existing paradigms of material optimisation to incorporate ideas of material substitution to be able to resiliently adapt to changes in resource availability as material flows fluctuate in the circular bio-economy.

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Author contributions

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DIALOGUES

DIALOGUE 1
MEEJIN YOON AND ANDERS LENDAGER
MODERATED BY METTE RAMSGAARD THOMSEN

Mette First of all, welcome to FABRICATE, Anders, and welcome back, Meejin. I believe you are familiar with each other's work, yet this is the first time you have met, which is very exciting. As you know, FABRICATE is a conference focused on the methods, technologies, and materials of making architecture. This physical nearness is at the core of the conference. This year, our call has sought to extend the discussion to include new perspectives on how fabrication changes in a resource-aware world. This brings forth both ethical-ecological and design-driven questions asking what the future value systems and practices of making architecture can be. The conference themes will expand on questions of how to work with reclaimed materials, what bio-based thinking can drive in architecture, and how resource-aware practices can be formed. I would like to start our conversation around how both of you work directly with materials. Anders, your work is about directly rethinking how materials can be reclaimed and reused through a second life in new buildings, and Meejin, yours is about careful consideration of how materials are deployed, what they perform, and what they mean. What do you think are the future practices of architecture, how will material thinking change, and what are the methods by which these changes can be supported?

Anders My whole practice started around a very similar question. It was a pragmatic start concerned with asking how we build resource-efficient and sustainable buildings, and how do they perform? We found a black hole with very few solutions for climate problems, political problems, resource problems, which made us realise there was huge potential for design innovation in the use of materials as new tools for architecture in meeting its sustainable targets.

Our investigations quickly identified the need for a new business model, which is not what I set out to do. However, to create the kind of architecture that was my goal, it became clear to me that a new business model was required. Today, I often say that I don't know if I have an architectural practice, but I know that we do architecture. In some ways we are an old typology – like where the master builder has control of every detail – and this is something that architects have not been doing for many decades. As Rem Koolhaas demonstrated at the 2014 Venice Biennale *Fundamentals*, practice has turned into a kind of catalogue architecture, where architects have been putting pieces together that are designed by others.

In our model we start to define what the premise and framework is for the project where each architect takes on a way broader perspective than usual, open to the possibility of creating new demonstrators that seek to address real and large impacts. We have gone from being part of the puzzle to defining what the puzzle is made of.

Meejin That's so interesting to hear. In thinking through shared values, and building those shared values for future generations, it is useful to pick up where you left off, Anders, specifically around the catalogue of parts approach versus having full control of the medium. As a discipline, we've shifted from an approach to sustainability that was primarily performance-based – the operational performance of buildings – to a more holistic approach to sustainability with a focus on the embodied energy or embodied carbon of the materials that we use.

When I was asked to design the Sean Collier Memorial at MIT, I had an opportunity to work with solid blocks of stone, even though the form could easily have been done out of concrete. Our design team's response was to use massive solid blocks of stone that stacked to form five half-arches – essentially 32 blocks in a compressive and shallow dry-fit vault. Working with large-scale solid blocks of stone connected us back to ancient forms of construction, and, while we used contemporary fabrication technologies to enable us to build the structure today, we were conscious that we were building a durable structure to last a century or more.

As everyone knows, renovating a building from the 1950s, 60s, or 70s presents many technical problems and challenges, as most of these structures were not built to last a century but rather for a duration in which systems and material assemblies would fail within decades. The lifespan of a building is tied to financing (often 30 years) and warranties (often less than 30 years) that are an intrinsic part of the building industry. The way we approach scales of time, given the range of technologies now at our disposal, from the most historic to the most contemporary, must focus on the finite resources on the planet. Many of our predecessors were speculating about this, but right now, with the tools at our disposal, there is a shared

'… THIS 'LOW-TECH' APPROACH TO MATERIALS IS REALLY GROWING ON ME. IT'S A DIFFERENT WAY OF SCALING …' ANDERS LENDAGER

understanding that demonstration projects with high impact are needed to advocate for and advance a different approach.

I'm curious to hear more, Anders, about the multiple ventures: how do these things scale? How do they scale in such a way that they're embraced, not just by architects, but by the broader community of enablers that will help steward the built environment now and across generations?

Anders It's inspiring to see how you are working with stones compared to poured concrete, and I'm very curious about it and it looks so beautiful. We have a project in Iceland and started a practice in Reykjavik. The notion of an island is an excellent prototype for our global situation, and even though we see ourselves as globally connected, the easiest way to really understand what we're doing globally is to look at a smaller community. In this case, we look at a large island that's a whole country, with few inhabitants.

Everything is imported in Iceland; everything comes from somewhere else. I asked some simple questions about materials and was told we have only one resource, an abundance of energy. I said, that's a pretty good start, but don't you have anything else? We have lava, I was told. I looked at the lava and scraped the first layer off, as it is porous from exploding in contact with air and moisture. The outer layer behaves like light concrete and insulates well; when you go deeper, you find a substance that's like the perfect concrete slab. So, we are now making local buildings out of lava instead of concrete, and this 'low-tech' approach to materials is really growing on me. It's a different way of scaling, this scaling potential of materials where we really understand that potential. The other part of where we are I call 'advanced low-tech', where we are rethinking discarded materials like concrete, wood, and glass, and reusing them as new materials.

Ten years ago, when I did the first prototype for a commercial building, I started to see that we could aim for high design standards and meet our client's budget by reusing so-called waste materials. These value chains were new, as were the partnerships required, as well as the design control mechanisms and ways of building. I felt like I needed to go beyond getting paid to design a building, but to also design a new process of building. So, we designed building materials and produced them as finished demonstrators for the contractor to match. Fees were paid in the normal way; however, we had created all these additional values of a circular economy. So, I found someone who invested a lot of money in all the ideas, and we are now scaling this approach as a product, like a new fabrication system out of waste. It's become a business model for architectural design that didn't exist before.

Meejin I think it is a perfect example of the values and innovations possible within hyper-locality. Even though we operate in a global system, with global economies, global manufacturing, and global supply chains, your project in Iceland demonstrates that a hyper-local approach to design and construction not only utilises immediately available

'… IT'S SO EMPOWERING TO REALISE THAT IN EVERY CONTEXT THERE ARE UNIQUE RESOURCES, LOCAL RESOURCES, AVAILABLE.' MEEJIN YOON

resources but creates new value and values. Thinking through a context where everything must be imported is fascinating, and it's so empowering to realise that in every context there are unique resources, local resources, available. Maybe our knowledge of building craft has also disappeared over time and needs to be reignited or reestablished or re-nurtured – maybe that's the right word: re-nurtured. And then we can think more holistically from circular construction and circular economy, to how, in the future, those materials could be reused again in yet more unexpected and different ways?

Mette I like to expand a little bit on this idea of hyper-locality and link it to the way you are working with resources. Anders, in your work you are tapping into very specific waste streams. For example, the finite resource of railway sleepers from the Danish railroad system. I think this is a good example, because you have your office on its premises and obviously have a good relationship with Danish Rail. You have made quite a few different buildings with these sleepers. But at some point, there will be no sleepers left. So, coming back to the problem of scaling up, how do you generalise from the specific resource flows you have worked with to something that can have a broader scope?

Anders It's a really good question, and one I have been asking myself. Over the last ten years, we have been refining the way we work with every type of reused material, from glass to wood and so on, and examining how they offer a new aesthetic and point us in a direction of measuring and adjusting performance. In this period, we have rethought our processes, shared them with industry, looked at their waste streams, and created greater efficiencies.

We are seriously interested in how these collaborations offer access to technology that can change what we can do. Right now, we are doing a project in Berlin in collaboration with INTERPANE, Europe's largest glass manufacturer. They have a machine that can split double-glazed windows apart and reassemble them as new windows. All of a sudden, ten years of prototyping becomes scalable. It is so important to experiment, rethink models, analyse mistakes and performance, and work towards a solution that will come. This is similar to what our practice has done with concrete bricks, or our latest work on recycling window waste, converting these complex geometries into a building material for our high-rise in Århus. Scalability is the most important issue for me, to achieve the largest impact for architectural design.

Mette This direct engagement with technology is compelling and obviously also something both of you share. Meejin, your work has long been driven at the intersection of research and practice and makes use of computational strategies and digital fabrication in advanced ways. Your work directly probes the potential of CNC tooling, integrated sensing, and advanced modelling. At the same time, Anders, your direct way of working with reclaimed materials reinvents material identity to create new building components. In preparing this interview, I saw this super fun video of you explaining how you used your car to drive over aluminium panels, flattening them to prototype the panelling for the TRÆ tower in Århus. How do you each think about the technologies you are using to make? Is there a specific role for low-tech and high-tech in your practices, or do you think there are more complex intersections between the two?

Meejin Sometimes our most advanced technologies today allow us to use renewable materials in ways that we couldn't do before. This not only allows us to introduce greater durability into building materials, but it also gives the architect more agency in working with materials, reducing the need to buy ready-mades off the shelf or from a mass producer. Often advanced technologies do enable innovation within historical frameworks for methods and modes of fabrication. Rather than binaries or intersections between high-tech and low-tech, I see it as a gradient of old to new, and new to old. Because they are now so estranged from us, some of the oldest forms of technology appear absolutely brilliant, fresh, and full of possibility. You ask: how did we forget this building technology in just a generation or a half-century gap?

Anders It's a very good point. It sounds like vernacular architecture; we're coming back to these local ways of building. Are there local technologies that you are adopting in your high-tech buildings?

Meejin I actually don't even think of our projects as high-tech. We use technology that's available to us in the context, but I would say especially when we build in different contexts in Asia. We think of building through an economy of means and local materials and working with local skills, using existing expertise and building knowledge. In some cases, we ask how we can use a minimum of material, as for the Helio House in Shenzhen, where we blocked out as much of the direct light as possible to reduce heat gain. I think these are the questions and trade-offs architects are making today. This prompts another question: how do we make these decisions? Do we have the right tools and data available to us?

Empire, State & Building, by Kiel Moe, looks at where all the materials came from to build the Empire State building. I feel like architects are increasingly concerned about tracing where the building materials they specify will come from. This goes back to working locally and utilising materials directly, as opposed to sourcing products from across the globe. In contemporary construction procurement, it is the contractors who are responsible for such decisions, and, although architects can try to control decisions on materials to some extent, ultimately and typically it is the costs that drive the decision-making on how materials are sourced.

As architects, one thing we're examining more closely is utilising all the tools at our disposal to minimise the use of material, aiming to do the most good as opposed to doing the least harm. Yet the profession is struggling with the conundrum of carbon-intensive material, as many structures rely on concrete, steel, aluminium, and so on. How do we shift to doing the least harm *and* the most good? In the US, we have the Living Building Challenge, which goes beyond sustainability, to address building for equity, producing energy on-site, and even growing one's own food. We're working on a Living Building Challenge project at Yale, which has brought forward many provocative questions around the frameworks to sustainability.

Mette The question of data is of course fundamental. You both work with data in integrated ways. Anders, your work relies on in-depth evaluations of your processes through Life Cycle Analysis and your very deep engagement with certification. Meejin, I noticed that much of your work integrates novel modes of simulation and, in the MIT memorial, also direct sense data. How are your data practices evolving? What is missing from the tools you are using and how can future practice informed by resource awareness be guided by information gathering, by whom, for whom, and through what means?

Anders This is a super question. As a student at Southern California Institute of Architecture (*SCI-Arc*), I was learning how to navigate a complex software programme by manipulating data in order to manufacture form: in other words, how to make a physical translation of a data scape. But this kind of design data alone is not sufficient to realise a building, when we start asking challenging questions about how to address building legislation, client input, financial requirements, production, or performance. If we want to use something that has no formal value, something we today see as waste, and want to move it into being a value asset, then an entirely different data set is required.

I've been asked to do a high-rise building in wood and waste materials, for a client who owns wind power parks. One of the biggest problems in the wind power industry is fibreglass waste. This drives many questions: how long do the turbine blades last? How do I take them down? Who is the demolisher of these structures? How do they transport them? Who incinerates them? What are the costs associated with all these actions?

'… DATA TODAY IS BASED ON DATA FROM THE 1970s … [AND IS] NOT ALWAYS RELEVANT FOR THE MATERIAL WASTE STREAMS THAT WE ARE WORKING WITH TODAY.' ANDERS LENDAGER

'IT FEELS LIKE ARCHITECTS ARE HAVING TO BE FORENSIC INVESTIGATORS AROUND THE SOURCING OF MATERIALS; AROUND HOW MATERIALS ARE PRODUCED AND THE AMOUNT OF ENERGY REQUIRED TO PRODUCE THEM, AS WELL AS TO TRANSPORT THEM.' MEEJIN YOON

All of these considerations necessitate a data set that we must build before we can develop a design that can later be approved by a municipality, by the fire department, by our client and contractor, and become a building component. What I'm trying to say is that our office is spending a lot of time on assembling information. It can be on air pollution or how corrosion classes limit the recycling of steel sheets in Europe. These data collection activities also necessitate a critical positioning. In our work, we are realising that much of our contextual data today is based on data from the 1970s. This data is not always relevant for the material waste streams that we are working with today. Our investigations take a lot of time but, once assembled, the data allow us to design with what we thought would be useless, without value, or impossible.

Meejin It's incredible that there remains such a gap in knowledge. Besides the basic properties of wood, steel, concrete, composites, and other such materials, other elements move us into the arena of chemistry, industrial production, and petrochemicals. There is no apparent index where we can fully evaluate which material might be better or worse. How are those materials tied to global supply chains, and the labour needed to produce them? In which contexts might child labour or indentured labour be prevalent? It feels like architects are having to be forensic investigators around the sourcing of materials; around how materials are produced and the amount of energy required to produce them, as well as to transport them. The food industry has come far in recent decades. Through required labelling, it's clear what's in the product you're consuming – even when you buy a coffee and a scone, you are informed about not only where the ingredients are from but also the calorie count.

Anders I like the word forensic: it's apt for many of the complex challenges that we are facing. We're just on the verge of starting this process in truth, and life cycle assessment is just one tool to start with, but it is full of inaccuracies. We overestimate our knowledge and we're not investing sufficient time in understanding this unnatural system, the substance of our urban condition, that *we* created. That's why we must harvest and understand waste as our new resource for building. It is important to investigate and question data that are feeding our growth-based economy. In practice, we often hear the maxim 'don't build', and in many ways I totally agree. We've built eight million square metres just in Denmark in 2023. So, what does that mean for 'don't build'? And are we ready to take this on today?

Mette I'd like to move the discussion to matters of skill. What are the new skills needed for these emergent practices of forensic data collection, material reinvention, and novel craftsmanship? Meejin, you have dedicated a large part of your career to academic leadership, and Anders, your outputs in so many ways act as lighthouse projects to the community at large. How do we build the lessons for a new resource-aware practice? What are the transferable skills that education and practice might exchange? Is there a need to change our curriculum?

Meejin We need both the academy and industry to be aligned in the right direction for there to be lasting positive transformation in the built environment. On the academic side, there are fundamental questions that can be asked that may not be possible for industry to ask. There are critical components of an architectural education, like the pedagogical format of the studio as a synthetic space where insights, speculations, and testing can come together at once. One thing that should be further enhanced in education is the ethics of building. So, how do you make ethical decisions around building practice? Knowing that there are finite resources, how do you make the right decisions about when it's better to adaptively reuse materials versus producing new? Will data be the answer? Can we afford to wait for better data? Decision-making in architecture is more complex and expanded than it was 20 or 30 years ago, and although the goal to leave the world in a better place than we found it remains, architectural education today is more explicit around building expertise in sustainability and building technology. It takes people like you, Anders, and others like Felix Heisel at Cornell, for pedagogy to be injected with inspiration and hope for a sustainable and circular future.

Anders When I was an undergraduate student at Aarhus School of Architecture, there was a great distance between academia and practice. As a Master's student at SCI-Arc, I learned that they could be much more connected because most of my peers were principals at my favourite architecture office. There was a deep connection between theory and practice, so your question is super important. Academia should be playing a way bigger role in this transformation. Its power is understated, and if it does not take seriously its potential to create and have impact, it will dissolve. Academia has more power to influence policy than practice. If you push thousands of architects out in the market that have a certain way of thinking and a certain way of building, it becomes a political tool. You are creating an organism with political power emanating from institutions that have access to the political process and who can lobby ministers on scalability.

Meejin Excellent! I would add that students are asking where is their agency, where does it exist in the discipline of architecture, and how can architects have more of it? I think this relates to ethics and values, and how the discipline can contribute to society. It's also easy to lose sight of how special and rare academic environments are, and how enabled an academic context is to explore and investigate these transformations. Education offers such rich experiences and explorations that can be scaled by the profession. The question of agency also ties us back to construction. In your practice, Anders, you've become the builder and the manufacturer. It seems that you have had to work across these roles because the construction industry was not willing to take on your ideas. The challenge that many young architects face is that they have all these talents and aspirations, they're taught these incredible skills, but feel a loss of agency. What advice do you have for students, Anders?

Anders Our most important task is to lead by example, to deliver projects that reset standards. I have high hopes for young architects and engineers. They are quick at finding solutions. They have a totally different mindset to previous generations. When I started 12 years ago, it was so difficult to find the right staff. I am impressed with how the educational institutions have changed and how they give students a great understanding of their own value, how they embed sustainable principles into design-led discussions, and how they offer each student freedom to operate critically. Architect Jan Christiansen, former mayor of Copenhagen, said: 'Remember that architecture is a restrained art form, and this restraint means that there's things that we can't do.' We must move away from this thinking, because all solutions are needed on the table now. It's a new time for architecture and architects.

Meejin I once heard that a Dean at another architecture school was challenged by the local professionals, who said: 'You're not training students well enough to come work for us.' And the Dean replied: 'I'm training your future competition; I am not training them to go and work for you.' I think this is the aspiration of education; our goal is to empower the next generation with knowledge and tools and methods so that they can do better than us.

Mette This is a really productive way to end our discussion by challenging our understanding of the agency of the practitioner and the power of academia. Thank you both.

'… OUR GOAL IS TO EMPOWER THE NEXT GENERATION WITH KNOWLEDGE AND TOOLS AND METHODS SO THAT THEY CAN DO BETTER THAN US.' MEEJIN YOON

DIALOGUE 2
KAI STREHLKE AND ANNA DYSON
MODERATED BY METTE RAMSGAARD THOMSEN

Mette Welcome to FABRICATE, Anna and Kai. I believe this is the first time you have met, which is wonderful. Your practices are quite far apart in a practical sense, but perhaps less so in terms of philosophy or outlook. I would like to probe how ideas of renewables, ecology, circularity, locality, and life span are informing your practice. To get started, I think it would be interesting to hear what you think of the focus on renewables, and therefore timber, as a solution to a sustainable architecture. What does abundance really mean? Do you see limitations? And what's the nature of those limitations?

Kai Blumer Lehmann was founded 150 years ago, and our serving CEO Katharina Lehmann is deeply aware of this history but also very interested in seeing what can be done with timber in the future. In the past 15 years, we have been part of a re-evaluation of the traditional values of timber, which dates back thousands of years, while at the same time innovating its technologies to create new possibilities that were not there 15 years ago. When I was studying, timber was perceived as a material to build family houses of one or two storeys. Now timber has become an urban material with which we can build multi-storey buildings and superstructures. In this way, we are finding entirely new possibilities for timber.

From a Swiss perspective, we have ten million cubic metres of timber that are being felled each year, but we only use five of them. So, at the moment timber is an abundant material because we could be deploying more timber in construction. At the same time, only 8% of construction is currently being built in timber. If we were to use all of the ten million cubic metres, this would only amount to 16%. So, timber cannot be the solution for all construction needs. And, yes, in this sense timber is not abundant. And there are more aspects to consider. The reason we have this volume of available timber right now is because we have very concrete issues in the forest driven by climate change. We have issues with fir and spruce species and specifically with the bark beetle, the effect of which is that we need to harvest a lot of material right now. This means that this perceived abundance in this Swiss context is highly unsustainable.

Long term, we need new solutions to help our forests to adapt to climate change, retain biodiversity, and change the species we grow to fit new temperature ranges. The abundance that you are referring to is specific to our situation now. We need to be prepared that in 10, 20, 30 years, everything is going to change. So, timber at the moment is one very important solution to sustainability, but we have to be ready that in the future this will be different. We need intensive research to understand how we can optimise the way we fell, the way we use the tree, and how we can increase efficiency and reduce waste.

Mette This is very interesting. I think this perspective on abundance allows us to think about bio-based resources in an ecological timeframe that includes interaction with other species and draws in the rhythms of growing and harvesting. Anna, your work has been focused on conceptualising this interrelationship between building and regional biomes. How do you see the new focus of the circular bioeconomy pushing new relationships between the built environment and the contexts of resource procurement?

Anna That's a great question. First, I would just like to reinforce that I would not want to participate in a timber versus no timber dichotomy. This is the problem with a lot of the discourse currently. We need to stop focusing on materials as outcomes and start thinking about the ecosystem. This is also what you, Kai, are addressing when you are talking about the need to match the functional attributes of species with potential products. Only then can we increase forest resilience, carbon sequestering, and biodiversity, while still thinking of the forest as a place of production of the resources we need.

For example, if we fell trees much more selectively, culling old growth and upcycling what we today think of as forest detritus, we can start to value what we currently dismiss as by-products. We need to think much more broadly about what the products of these ecosystems are and how we participate in managing them. We have a lot to gain in researching and developing new methods to upcycle these by-products, in terms of increasing the potential resilience and carbon-sequestering abilities of regional forests, but far more aggressive investment is needed. This also includes bio-based products that could be included in the mixtures of non-renewables such as cementitious materials to help them become more circular and reduce their carbon impact.

An important aspect about timber is that it is exceptionally reusable. Even from a North American perspective, we have timber-built houses that are several hundred years old. What I mean is that we have timber stock directly accessible in our built environment that we need to find ways to reuse. Timber is extremely durable, and it's also recyclable if we design for disassembly and reassembly. This is a huge benefit of timber that is often unsung. We need to widen our understanding of ecosystems and think about how the broader circularity of biomass systems can be incorporated. If we treat buildings as material banks, we can store carbon in biomass structures. If we cull old growth, we can allow new growth and mid-sized trees to sequester more carbon. A lot of people don't like to see old trees go, but sometimes they can be more useful in our buildings and allow for forests to be more productive overall.

As you know, I am inspired by Eames's scalar thinking. In this sense, if we zoom out 30,000 feet, we should not be thinking about whether to build in timber. Instead it is about how we can move with the rhythms of regional biomes, and how we can support our forests to become more resilient by carefully managing the carbon cycling overall, which means matching the cultivation and culling of specific species at the right time.

Mette I think this question of how to think of biomass holistically is very interesting. It challenges us to engage the entirety of timber mass as a resource for construction. Kai, are you involved in projects that are looking at reusing or reclaiming timber?

Kai Blumer Lehmann consists of many different departments. One of them works with modular architecture. Here, we have been collaborating with the City of Zürich to develop modular school units. This is an interesting case. In Zürich, we have a widely varying demography that creates a big demand for schools in one area, which 10 to 15 years later will subside because people are growing older. With the city, we have been developing design-for-disassembly modules that can extend a school for a period and then be taken down and erected elsewhere. In this way, we can recycle these units at their highest design value. This is an important part of circular design thinking – when we recycle, we need to consider the

'WHEN WE RECYCLE, WE NEED TO CONSIDER THE OBJECT OF RECYCLING, AND THE LARGER, THE MORE INCLUSIVE, AND THE MORE INDEPENDENT IT IS, THE MORE VALUE IS RETAINED.' KAI STREHLKE

'WITH PARTNERING AND A SMARTER USE OF RESOURCE, WE CAN INCREASE THE BIODIVERSITY OF BOTH AGRICULTURE AND FOREST, WHILE INCREASING BIOMASS FOR THE BUILDING INDUSTRY, CREATING A RECIPROCAL, CYCLICAL RELATIONSHIP.' ANNA DYSON

object of recycling, and the larger, the more inclusive, and the more independent it is, the more value is retained.

Another perspective is to build for longevity. In the Cambridge Mosque (see FABRICATE 2020) we are creating a project that is unlikely to be used for any other purpose but is designed to last for hundreds of years. This is another vitally important point: we must design to make buildings that reduce consumption and last as long as possible.

Finally, we are interested in readdressing the number of processes we use when we construct. We are at present working on a project with Herzog and de Meuron that is constructed in wood and rammed earth. Here, we are working to decrease the number of processes required to an absolute minimum.

Mette So, is design for disassembly and adaptation leading us to a new ethos?

Kai Yes, the idea in modular architecture is that you need to think about what you can put on a truck, where all connections are standardised and simple. This would be much more difficult with concrete construction. Still, I think we have to be careful, because if we only think through recycling and plan for reuse, then we are missing a much more impactful measure. The more important goal is to facilitate use that can last a long time, thereby reducing the grey energy of continuous assembly and disassembly.

Mette This is really interesting, especially set against the 'don't build' dogmas that we hear about so much. I think the converse 'don't destroy' axiom has more impact, because it's about the incorporation of ideas of change and evolution. I wanted to bring us from the discussion on forestry to the idea of locality. At Blumer Lehmann you take pride in working with local, Swiss, timber and connecting where the materials are sourced to its fabrication and full deployment through cascading. It's a sort of closed-loop relationship of localising and using resources.

What is the importance of locality in your practice, and how does it impact the quality of the products that you make?

Kai Switzerland is an expensive country, so there's big pressure on importing cheap wood from, for example, Russia. Meanwhile, we have to harvest Swiss forests because they are decaying because of climate change. In Switzerland we label local timber as Swisswood, which supports local circularity, keeping the entire value chain of the timber industry inside one country. But local materials are of course more costly, and we need clients who are sensitive to the overarching value that this local circularity produces.

At the same time, we are active in global markets, and whenever possible we use local resources. Buildings like the Cambridge Mosque in the UK or the Apple HQ in Bangkok are helping to foster local timber economies. For the Haesley Nine Bridges Golf Resort in Korea, for example, there was a requirement not to import all timber components from Switzerland but to try to use the building as a catalyst to grow local industry. The goal for the future should be to use local materials and resources.

Mette Anna, how does locality inform your practice?

Anna First of all, we can hardly say 'don't build' in emerging economies where there's a great need to improve and increase the building stock, and where local emissions are a tiny fraction of global emissions. That's a non-starter. But future building practices need to contribute to the resilience of regional forest ecologies. Kai is giving a great example for how building managers can become key instigators and change agents, as has recently been written about by Osborn *et al.*, in Canada. They show how builders could partner with forest managers in the specification of building products, creating a relationship between resource and specification. Partnering is really the key message, between forest managers and building product producers, making sure that wood and other biomass materials are not being left to decay and escalate global emissions. So, we have to evolve from business-as-usual forestry. It is the same message for agriculture. We have to intensify the biodiversity of agricultural tracts because there is so much land globally that has been deforested that doesn't necessarily need to be deforested. With partnering and a smarter use of resource, we can increase the biodiversity of both agriculture and forest, while increasing biomass for the building industry, creating a reciprocal, cyclical relationship. This is what Kai is describing in Switzerland, but there are other examples in Japan, Canada, and elsewhere.

The big danger is that we won't follow these examples. In many regions, they don't have the biome to sustainably produce timber for building; we need to better value other resources

'LEARNING FROM ECOSYSTEMS IS TO CREATE HIGHLY DISTRIBUTED – AND THEREFORE LOCAL – RESOURCE MODELS.' ANNA DYSON

like small bamboo for woven-type structures, low-fired bricks, or reinforced earth. Demonstrations like the Cambridge Mosque elevate the image of bio-based processes and sustainability for long lifespans. They create a positive core relationship between good architecture and architecture that's durable.

I'd like to relate the concept of multi-functionality in working with ambient ecosystemic resources – the water, energy, materials, and food life cycle within a regional setting. At Yale Center for Ecosystems + Architecture (CEA), we think of our work as 'biomechanical Frankensteins', meaning that we aim to transition towards biocompatibility with hybrid systems that still reuse or reposition the materials and logic of our conventional practices. However, we are trying to learn from natural ecosystems to understand how ecosystems are building relationships and what the rhythms of these relationships are. For example, we ask how do ecosystems metabolise energy? What is the discrepancy between these and prevailing anthropogenic systems, and how can we metabolise in the way ecosystems do? Today, most of us live in places that are not yet sustainable without the concentrated energy flows that are produced by the combustion of fossil or bio-based fuels. Our work seeks to understand how energy systems could be drawn from direct ecosystem interaction, but that means that materials and energy would be synergistic. We are analysing biological relationships in order to move with them and produce the outcomes that we need for basic sustenance. Yet, it is at present nearly impossible to transition from a predominantly mechanical paradigm into a fully biological paradigm. We are still in kind of a bioinformatic revolution right now. To fully transition into a biological paradigm, we need to understand the way ecosystems work through radical redistribution. Ecosystems don't work with concentrated energy, or other resources for that matter. Learning from ecosystems is to create highly distributed – and therefore local – resource models.

In this way, our projects are investigations as to how to think of new relationships. Yes, we have patents, and people commercialise our systems, and yes, we do want to solve problems in the near term, but we never think about them as ends, in and of themselves. We see them as instantiations of investigations into ecologies.

Mette I want to return to your argument for intensifying agriculture. I understand this through the idea of making more space for forests and biodiversity by allowing the built environment to become a multi-functional place for energy collection, resourcing, and food production. Can you say more on that?

Anna Establishing new interrelationships between species is central to our work. In cities like New York, people spend up to 90% of their time indoors. This has been de facto a radical experiment into living in low biodiverse environments, that pertains only to our very recent past. As a species, we have evolved over the course of millions of years in interdependency with other species. For example, what are we breathing in the spaces we are occupying right at this moment? We're breathing the oxygen from plants that might be miles away, but we are also inhaling the aerobiome, which is made up from the millions of microorganisms within a given airspace. The aerobiome is basically a distillation of our relationship to other species. But within urban ecologies, the aerobiome we breathe is indoors and low in biodiversity, which is catastrophic for human immunity and wellbeing. Thus, we have no choice but to intensify the reintroduction of other species into our urban environments, which could also be synergistic for food, air, and water quality, and biomass material flows that could be redirected.

The contemporary crisis is ultimately about understanding biodiversity, understanding the interrelationships between all species. We could also be thinking about reinserting ourselves in the ecosystem as well. When we talk about the management of timber, we need to shift from isolating and objectifying it as a product. There are all sorts of physiological responses when we are enveloped in a biodiverse environment. It is not only about placing food production in the urban environment, but more fundamentally trying to re-find the interrelationships between our species and the biomes we are participating in. These relationships are so subtle and difficult to fathom. Just brushing against leaves might change our microbiomes indoors. Because we have spent thousands of years separating ourselves from biodiverse ecologies, we have created acutely low microbiome environments within our buildings and cities. As architects, we don't yet know how to design with microbial ecologies. However, we are learning. There are some very interesting lessons that date back to the 60s and 70s, when NASA took a piece of earth to outer space and realised that they couldn't recreate human living conditions without plants. So, they started really studying these closed-loop environments and, instead of mechanically filtering the air, like we try to do within modern buildings, they deployed plant-based systems to 'metabolise' the biochemistry of the air to make it breathable for the astronauts. It was a complex investigation into the intricacies of our interdependence with other species, and very definitely an acute warning of their essential role in our own future survival.

At Yale CEA we are collaborating with several different universities and national labs to understand the built environment as participants in very large open biomes. Conversely, we want to understand what we are doing to our own biology by closing ourselves off in urban indoor environments, and what the potential new relationship with biodiverse ecosystems can be: how can we design *with biodiversity*, towards living architectural systems?

So, to return, Kai is giving an essential example of growing to build. We can expand these ideas of building partnerships to the way we design our cities as interactions between living systems, with living biomass and real exchanges between species.

Mette I was wondering if we could come back to the point Kai made about the timber species and climate change. Here, we are also responding to change. The way you describe it, we seem to be in some sort of bell curve. While we need to use the timber that we have now, we are also going to have to grow other species for future usage. What species are there? How are they different, and will they perform differently?

Kai Putting it simply, in the context of climate change, it's species that are more resistant to heat. But it's not only about species, it's about biodiversity. Returning to the context of Switzerland, then, about 50 years ago, the apple-growing industry gave 50 CHF to each farmer who chopped down their apple trees. It happened on a vast scale and destroyed a lot of biodiversity. What drove it was mechanisation. Traditionally apple trees were planted in island configurations, with apple trees planted every 20 to 50 metres. The result was a completely different landscape with a completely different biodiversity than what we have now.

Today the forest has many different roles that it needs to manage. One is biodiversity, one is a place of production, giving biomass for our society through timber, for example, and the last one is recreation. Often, we see these roles compete. I totally agree with Anna when you say if we have old trees and we take them out of the forest, it sounds sad. But these old trees do not capture so much CO2 anymore. Therefore, it makes sense also from an ecological point of view to use this timber for construction and have other trees at the same place taking the space and capturing more CO2.

Mette I think this idea of separate roles is very important. Anna, you have talked about the desire to challenge a solutionist dogma. However, it is difficult to think about these roles without wanting to functionalise them. How are you ideating approaches that position us within ecological cycles that are not only for our functional benefit?

Anna That's what I think is really critical: we can't reduce the biological environment to one function, or a set of functions. We don't make a distinction between abiotic systems and biotic systems in our research. They are essentially always coupled, in space and in time. Architects tend to think about resources from the moment we extract them and across their life cycle. But we need to zoom out and think about the fact that we exist in geological time too. We need to conceptualise the work that it takes for the geo-biosphere to produce sand, or produce a tree, and how it is impacted by its relationship to everything else. If we understand that we're not designing just for ourselves, and we're not just designing for this moment, then we cannot continue with the mechanical mindset, where design is a means of controlling relationships. Instead, we need to engage the complexity of recursive relationships between multiple species and between environments and species.

Mette I'd like to end by returning to the question of abundance. The European Green Deal and its emphasis on circular bioeconomy positions renewable resources as essentially abundant. However, we know that this sense of abundance is fundamentally false. How can we address the axiom of abundance in the circular bioeconomy and discover other ways of thinking about renewable resources for architecture and the built environment?

'... WE CANNOT CONTINUE WITH THE MECHANICAL MINDSET, WHERE DESIGN IS A MEANS OF CONTROLLING RELATIONSHIPS. INSTEAD, WE NEED TO ENGAGE THE COMPLEXITY OF RECURSIVE RELATIONSHIPS BETWEEN MULTIPLE SPECIES AND BETWEEN ENVIRONMENTS AND SPECIES.' ANNA DYSON

Kai We have to find more intelligent ways to manage forests and be aware that they are in constant change. Decisions we are taking now are not going to be valid in 10 to 20 years. For example, how we are now trying to find systems where we are using different materials that are working together more intelligently. We need to find synthesis between materials like earth and wood. We can see that they work very well together. At the moment, prototypical earth buildings are expensive, but this will improve, and it's going to be very interesting in the future. It's something we possessed hundreds of years of knowledge about, but which is now almost completely lost. We must rediscover these relationships.

Anna I absolutely agree. We have to reinforce coordinated support of all of the different actors across the life cycle. We can't achieve radical change that is biocompatible unless we support the actors. From material producers to designers and owners of built environments. We must really shift our methods towards circularity and biocompatibility. We've got the biomaterials, but now we must shift towards bio-based processes and the overriding message of circularity, material flows, and durability.

We have some amazing examples like Kai's practice, where we have a very tightly coupled relationship to a regional biome that has a deep tradition of timber building that is also being revolutionised along circular lines. This is amazing. In our UN report we're recommending a shift towards bio-based processes where they can be regenerative, but the overriding message is really about circularity. I think we really have to conceptualise this idea of flow. Material flows in our prevailing economy are mostly geological and extractive at this point; again, this is only our very recent history. We only have to go back to the early 20th century to see a time when the overwhelming bulk of global material flows were local, bio-, and earth based. That is how we built up major global cities prior to 1945. But today, the preponderance of global building materials and methods are mineral-based and they're massive. We've created that. So, how do we respond now?
I think that the biggest problem with our discipline is that we're still so incredibly isolated. We like to think of ourselves as the last generalists, or the expert integrators, but I would challenge this. How do we really interface with other practices? Much of the most lauded and prestigious architecture of our recent past has treated other disciplines as consultants and maintained top-down hierarchies. This is not representative of the interdisciplinary knowledge required to take on the environmental challenges that we're facing in the 21st century. We really have to change the way we are working and bring in multi-disciplinary teams as true partners in the conceptual process from the beginning. Who will support the transition to such a model? We need to get together with policymakers and other decision makers who can support systemic change, to ask really fundamental questions about what built environments are, and what architecture is, as a kind of societal activism. For me, one of the biggest challenges is how do we shift our own culture to be a lot more inclusive?

Mette Thank you so much. The conversation really opened up in a very generous way. It's been so interesting to hear from both of your points of view.

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DIALOGUE 3
CRISTIANO CECCATO AND ZHU PEI
MODERATED BY PHIL AYRES

Phil Welcome back Cristiano and welcome to FABRICATE Zhu Pei, it is a pleasure to have you both here. You have both been responsible for significant building projects in China, so it will interesting to draw upon your experiences and insights from this context, particularly with respect to our focus on how amplified resource consciousness impacts design and fabrication. I would like to start with the fact that the impact of the building industry on climate change is now both widely acknowledged and well-quantified. How is this acknowledgement playing out regarding changes to your respective practices? What are your experiences with the contexts in which you are working?

Cristiano Let me provide some context, particularly focusing on our work in China. Environmental sustainability ratings often require attention not only to efficient building physics and performance, but also to the sourcing of materials. This practice has two implications. First, it reduces the transportation distance for materials, which is beneficial. Second, it empowers local and regional economies. Importantly, using locally produced materials ensures they align with a cost framework that we can control and a quality framework that is well understood within that local context. In the case of our projects in China, such as the new Daxing Airport in Beijing, we leverage well-established local solutions. For example, the roof of the airport is a form-found amorphous shell constructed using mega-spaceframes, a method clearly understood and commonly used in Beijing. By applying a form-finding algorithm to this existing structural system, we achieved a natural sagging roof that allowed for maximum flexibility in the interior layout, essential for long-term resilience without the need for major structural demolition. In collaboration with our local partners, such as the BIAD (Beijing Institute of Architectural Design), this approach instilled confidence in the local construction industry's ability to complete the project within fixed timeframes and cost parameters.

‘RATHER THAN SOLELY LOOKING FORWARD, I OFTEN LOOK BACK TO TRADITIONAL AND ORIGINAL STRUCTURES, SEEKING INSPIRATION FOR ADAPTING THEM TO MODERN SITUATIONS.’ ZHU PEI

Another project in Beijing, Galaxy Soho, exemplifies our approach to material selection. At the client’s request, we used readily available 3mm powder-coated aluminium for the exterior cladding. This choice ensured a competitive price in the market and the ability to achieve the required curvature using cost-effective, locally implementable, developable surfaces. Our careful consideration of the local construction industry’s skills and capabilities ensured a successful outcome. These examples highlight the importance of tailoring designs to the local construction industry, not only for proximity but also to leverage the skills and capabilities of the region. This approach minimises the risk of unfavourable outcomes and ensures successful project delivery. While we have undertaken various projects globally, these examples from China illustrate the significance of adapting design strategies to the local context.

Zhu I believe addressing this issue is crucial, as it poses a significant challenge when working on projects. Personally, my exposure to large urban structures, especially in the central urban areas, has been limited. One reason for this limitation is the scale of the projects I typically engage with. Additionally, my focus lies in rediscovering possibilities within local capabilities.

When approaching projects, I prioritise exploring the potential of traditional structures and materials within a contemporary context. Rather than solely looking forward, I often look back to traditional and original structures, seeking inspiration for adapting them to modern situations. This approach stems from a unique mentality in my design process, where I strive to draw from local inspirations first.

Climate is also a critical factor in my work. Considering China’s diverse geography, ranging from humid and hot areas like Jingdezhen to arid and cold regions resembling deserts, I must tailor my designs to fit these distinct climates. Right now, I am involved in a project – the Majiayao Pottery Ruin Museum located in Gansu, northwestern China – which contrasts significantly with the Jingdezhen Imperial Kiln Museum in terms of climate, culture, capability, and available resources.

For me, the challenge is to adapt to the construction culture of each region and draw inspiration from traditional structures and materials. Even when working with older materials, I strive to find contemporary applications. This process is quite different from large-scale projects like Daxing Airport. Despite the smaller scale of my projects, I face unique challenges, building in vastly different regions, ranging from dry and cold to tropical climates. These diverse environments force me to reconsider how to approach construction intelligently and sustainably while leveraging locally accessible materials and resources effectively.

Phil It’s intriguing that both of you have brought up the significance of local resources not only in terms of materials, but also regional knowledge and capabilities. How do you acquire an appreciation of these regional level resources for your projects, and how does this inform your approaches to procurement?

Cristiano When discussing local regional procurement, particularly in China, our approach is driven by the exceptional quality of the construction industry in the country. With nearly 100 people across three offices in China, all actively engaged in many projects over the past 12 to 15 years, we have developed a comprehensive understanding of attainable solutions. This allows us to tailor our construction designs to suit the local context. In my experience, the issue of global supply chain constraints is somewhat less applicable in China. I recall that, during the 2008 Olympics, large-scale projects like the Bird’s Nest and CCTV required substantial amounts of steel. The central People’s Republic of China government had to manage the allocation of steel because of its scarcity at the time, and required international sourcing. While this specifically refers to rolled section steel rather than a spaceframe, it highlights the challenges of building on a global scale.

One significant concern that impacts projects globally is the fluctuating price of materials, particularly steel. To address this, the team will often secure steel contracts early in the project or include an option on the steel before the design is finalised. Locking in a price early provides cost control, especially if steel prices increase during the later design stages. It’s a delicate balance between designing for the local construction industry, material availability, and long-term cost considerations.

Currently, we are working on a project in California, and our approach is entirely focused on local constructability. This decision is influenced by the fact that locally based contractors will be handling the construction. Presenting them with a design that worked well in, say, Beijing wouldn’t be practical, as it might not align with their local practices, exacerbating risk and cost. Understanding this local context helps strike the right balance between innovation and ensuring cost, quality, constructability, and timeline certainty. Ultimately, successful project completion is the goal, and finding the sweet spot in these considerations is crucial. To facilitate this, we make an effort to address procurement considerations as early as possible in our projects. It’s an aspect that warrants further discussion, perhaps in a future conference. Procurement methods vary – be it in design-bid-build, design-build, or progressive design-build, or else under public-private partnerships. Each approach comes with different pressure points regarding project governance. For instance, in cases of early contractor involvement through design-build or a pre-construction services agreement, where the contractor’s insights guide the design phase for constructability, it’s important to have a dialogue with the client and industry stakeholders. In the case of Galaxy Soho in China, the client involved façade contractors early on to ensure constructability and desired quality.

Finding the sweet spot in this dynamic requires a collaborative approach with the client and industry players, understanding the procurement process, and considering aspects like achieving a guaranteed maximum price in the contract. It’s not uncommon for individuals to be surprised when their preferred procurement method clashes with contractual obligations. Therefore, early design considerations must align with the chosen procurement framework to avoid a disconnect between ambition and practicality.

‘I ADVOCATE FOR A BALANCE BETWEEN LOW-TECH AND DIGITAL TECHNOLOGY. WHILE TECHNOLOGY IS INDISPENSABLE FOR THE CONSTRUCTION PROCESS, IT SHOULD COMPLEMENT THE ARCHITECT’S CREATIVE AND ARTISTIC VISION RATHER THAN REPLACE IT.’ ZHU PEI

While contemporary design discussions often revolve around advanced technologies like robots and computerised form generation, it’s essential to acknowledge that these tools only become meaningful when integrated effectively into the procurement process. Understanding procurement mechanisms provides architects with greater control over interfacing with the construction industry, thereby ensuring desired outcomes contractually. This aspect deserves more attention in future conferences.

Phil Zhu Pei, your practice is deeply committed to working with local knowledge, resources, and materials, and, from this foundation, produces outcomes that exhibit real innovation. How do you achieve that on the ground working with local contractors?

Zhu My design philosophy emphasises deeply connecting projects to the local context. This is why I focus on being fully engaged in every step of the design process. For instance, I often don’t have a specific contractor but rely on a general contractor. This means I handle tasks like curtain wall installation myself, since clients often don’t budget for these details; this allows me to explore cost-effective options while maintaining the overall design integrity.

Several key aspects are crucial in the construction of my projects. First, I place significant emphasis on creating mockups. Construction teams may lack the craftsmanship needed, often resembling farmers more than artisans. Mockups, in my experience, serve as a pivotal tool for cultivating and training individuals to execute the project according to your vision. Second, digital technology plays a pivotal role, especially when dealing with intricate designs. Notably, the Jingdezhen Imperial Kiln Museum, with its complex architecture and subtle double-curved structure, underscores the importance of both these aspects. The project posed challenges in pushing construction to its limits, with each segment exhibiting varying sizes and curvatures. To overcome this, digital technology became essential in driving the construction process. Collaborating with contractors, a specialised, adjustable, and movable scaffolding system was developed, relying on digital technology to adjust the scaffold’s position and shape incrementally, ensuring precise construction. Despite the critical role of technology in the construction process, I firmly believe that technology should not dictate design but rather aid in the development of construction processes. For instance, in creating the museum’s model, I initially restricted the use of 3D printing, opting for a hands-on approach to build the complex double-curved shape. This manual approach instilled confidence in the team and adhered to the principle that architecture must be based on systematic construction methods.

In the design philosophy, I advocate for a balance between low-tech and digital technology. While technology is indispensable for the construction process, it should complement the architect's creative and artistic vision rather than replace it. Technology serves as a tool to facilitate construction, ensuring efficiency and precision while allowing architects to retain control over the artistic and poetic aspects of the design. The fusion of these elements, from my perspective, defines the critical role of imagination and creativity in contemporary architecture, rather than technology.

Phil Cristiano, procurement has been a core focus in this discussion – how do digital technologies support this process for you?

Cristiano To begin with, it's important to clarify that we are architects and not contractors. In the past, the architect and contractor roles were often merged in the concept of a master builder. This meant designing based on a deep understanding of what was buildable. However, the modern Architecture, Engineering and Construction industry is highly fragmented. In our work, especially in our collaboration with the aviation industry, we've observed how supply chains can integrate tightly with the design and engineering process. This integration is gaining traction in China with the rise of a promising transport industry. Successful design in this context involves close collaboration with those responsible for actual construction, ensuring alignment between the design and the expected performance of the structure.

A common issue, even in our office, is the tendency for people to design without a thorough understanding of construction processes. Designers often claim they can rationalise constructible geometries and make a design buildable without truly comprehending the construction industry's nuances, which is potentially risky for a project. For example, a project in New York City involving cold-bent glass exposed how warranty challenges, not the glass-bending process, posed the most significant hurdle to procurement. The client sought a 25-year warranty for glass sealant, while the fabricator was only comfortable with a ten-year warranty. This discrepancy led to increased costs and risks for the contractor. Such situations underscore the importance of understanding fabrication processes and challenges before settling on a solution.

Designing with digital technologies is hugely beneficial, but cost implications must be considered. For instance, on a project in China, we spent six months travelling right across the country, researching metal factories to assess their capabilities. Challenges arose from the standard sizes of sheet aluminium coils available in China and local limitations in cutting technology. To navigate these challenges, we rationalised

'SUCCESSFUL DESIGN IN THIS CONTEXT INVOLVES CLOSE COLLABORATION WITH THOSE RESPONSIBLE FOR ACTUAL CONSTRUCTION, ENSURING ALIGNMENT BETWEEN THE DESIGN AND THE EXPECTED PERFORMANCE OF THE STRUCTURE.' CRISTIANO CECCATO

the design based on cone geometries, ensuring it could be executed with available technology in China and within the client's cost and time constraints. This approach places a responsibility on designers to align their vision from the outset with practical considerations. We dedicated substantial time to travelling across Guangdong, Liaoning, and Beijing provinces, gathering company information and reflecting on its implications for our design process. The goal was to provide the client with a genuine sense of confidence and assurance that our design could be feasibly executed within the three established project parameters – cost, time, and quality. This process of investigation is vital, as it aligns with our architectural responsibility. China boasts capable design institutes, and we prefer to engage them in a meaningful dialogue early on, rather than merely presenting our concept and expecting them to follow suit. In other words, maintaining control over the design process is crucial to us. You can aim for innovation and pushing boundaries, but you have to do it in a way that allows you to stay in control of the process.

Phil Zhu Pei, your Imperial Kiln Museum stands out as a wonderful example of valorising and reclaiming existing materials. Building upon the concerns around liability and warranty that Cristiano just raised, what are the particular challenges that reclaimed materials present here, and how did you navigate these for the project?

Zhu In deciding on materials for construction, I find two key considerations. First, I draw inspiration from traditional brick kilns, a practice dating back to ancient times where craftsmen built structures using bricks. I am passionate about preserving this cultural idea and have chosen to use bricks in my designs. The second challenge arises when attempting to blend this construction tradition with contemporary architecture. A primary decision lies in the choice of a structural system. Whether in China or Europe, using solely brick vault may not adequately resist forces like earthquakes. For instance, in the Jingdezhen region, where earthquakes are a concern, this necessitates a solution beyond brick vault to counter horizontal forces. Even with our smaller-scale brick vault projects, fulfilling earthquake resistance tests remains a challenge.

In projects like the Jingdezhen Imperial Kiln Museum, I consider using bricks not just for their technological construction aspects but also for their cultural significance. I contemplate incorporating concrete in the arch structure to create a two-layered brick sandwich. This, to me, represents a deep integration of my design into the local culture and climate. My goal is to build in a way that is not only aesthetically pleasing but also environmentally sustainable, in light of climate change. Additionally, I value the power of tradition and believe that we should not disregard it. For example, observing traditional construction methods, such as building brick art without scaffolding, impresses me with its ingenuity. The local deep understanding of materials and sustainable practices, like using recycled old brick, fascinates me. The narrow alley and vertical courtyard forming the wind tunnel and chimney effect in local housing offers insights into sustainable design solutions. I strive to rediscover these smart approaches and apply them in my architecture. An achievement I am proud of is that the Imperial Kiln Museum, a building area more than 10,000m² in extent, operates without air conditioning, even in the hot and humid summers. This accomplishment highlights my commitment to passive design strategies and environmental responsibility.

'THE LOCAL DEEP UNDERSTANDING OF MATERIALS AND SUSTAINABLE PRACTICES, LIKE USING RECYCLED OLD BRICK, FASCINATES ME.' CRISTIANO CECCATO

Phil I really appreciate the way you are enriching the conversation about reclamation here beyond it being a climate or resource scarcity imperative and connecting it to being a practice rooted in extending tradition and creating cultural resonance. Cristiano, do you see the need for working with reclaimed materials becoming a necessity and forcing transformations in how we construct?

Cristiano Well, you can reclaim some materials. For instance, we've incorporated reclaimed wood and even utilised building rubble as a concrete aggregate for certain projects. Zhu Pei's example, with its poetic and beautiful reference to the project's history, is noteworthy. Allow me to share a different example involving the modification of construction techniques. In Taiwan, on the Danjiang Bridge north of Taipei, we employed a conventional material – concrete. The client preferred a slipform process to construct the main tower of the bridge. Our design vision aimed to express the tower's structural forces within the dynamic form of the structure, thus transitioning from a curved convex to a curved concave profile as the tower ascends. This meant a different formwork geometry at each vertical step of the slipform process. Traditionally, creating separate formwork for each profile would be both cost-prohibitive and time-consuming. Collaborating with PERI®, a renowned formwork fabricator from Germany, yielded remarkable innovation – a variable geometry formwork system driven by coordinates from a computer, which controlled the form of the phenolic shell using strand jacks. Consequently, the formwork adapts its shape as the structure ascends. Through this innovative approach, we were able to adhere to the use of concrete, an established material with predictable pricing. The result is a sweeping form that changes profile, achieved at the same speed and cost as a straight structure.

This project underscores the importance of pushing technology to achieve specific design goals. Early engagement with PERI® and collaborative workshops with our German engineering design team at Leonhardt, Andrä & Partner and the Taiwanese executing team from Sinotech were integral to understanding the fabrication process. While not focused on reusing materials, this approach extends the capabilities of an established material technology, such as cast concrete, by pushing its limits. While I haven't had the chance to work on a project like Zhu Pei's kiln museum, exploring opportunities to rethink materials and processes remains a compelling avenue. His ability to push the boundaries just a little further, even with traditional materials, is a commendable achievement in itself.

Phil Given what we have been discussing, I'm interested in hearing what you feel the implications are for education?

Cristiano Well, in my view, the effectiveness of architectural education depends on factors such as the institution you attend and your learning goals. As a young student, you often enter university without a clear understanding of what you really need to learn. For instance, during my undergraduate programme at the Architectural Association, I encountered frustration arising from the lack of cohesion between advanced design concepts and practical skill development. This disconnect stemmed from educators who themselves had limited experience in a professional practice. In the UK, there's a distinction between education and training – the former at university and the latter on the job. My own journey involved contemplating difficult concepts in education and then learning practical aspects in practice. To enhance their

'COLLABORATION IS KEY – ARCHITECTS NEED TO UNDERSTAND HOW TO WORK EFFECTIVELY WITH ENGINEERS, CONTRACTORS, FABRICATORS, AND CLIENTS, TO GUIDE A DESIGN TOWARDS THE ARCHITECT'S VISION.' CRISTIANO CECCATO

architectural education, students should have the freedom to explore contemporary digital technologies, experiment with various fabrication techniques and even devise new ones. However, it's crucial to consistently relate these explorations to their application within the broader architectural profession and construction.

Architects can design using these techniques, but they lack ultimate control, as they are not contractors. Professional indemnity insurance strictly prohibits architects from assuming this role. Therefore, students must integrate their knowledge into their designs so that contractors can easily understand and execute them well. Collaboration is key – architects need to understand how to work effectively with engineers, contractors, fabricators, and clients, to guide a design towards the architect's vision. Without this collaborative approach, architects risk having isolated visions, unless they have the rare luxury of being able to select their preferred contractors. For most architects, success lies in embedding knowledge of constructability into their designs through collaboration with other project partners. Early awareness of this aspect is vital for the long-term successful development of students.

Zhu I agree that it depends on the type of school. Take the Central Academy of Fine Arts, School of Architecture, in Beijing, for example. I am Dean of this school and I want to clarify our vision and goals. Art schools, such as my school, may not have an advantage in technological and scientific research, but we need to understand our unique strengths and objectives. Our educational approach should not simply follow the traditional academic model; instead, I am keen on creating a school with a distinctive character. My emphasis is on cultivating creativity and imagination among our students. I believe there are three key aspects to achieving this. First, students should be encouraged to explore the past, understanding masterpieces, construction cultures, and cultural contexts based on historical awareness. Second, they should be encouraged to develop digital skills and explore the potential for the future of architecture. Third, students should gain a perception of architecture as a unique form of art, distinct from visual arts like painting and sculpture, focusing on aspects such as time, space, materials, and structure.

Our school encourages students to cultivate a historical perspective, appreciate the nature of architecture and the creativity it contains. This includes a focus on the architectural essence, prompting students to love their work and use both their hands and minds to cultivate interesting imaginations. In my six years of leadership, I've implemented reforms to make our school smaller in size but more focused on architecture itself. I feel that education, globally, is deviating from the essence of architecture, neglecting aspects like construction, materiality, and history. While there's nothing inherently wrong with this shift, it deviates from what, in my mind, an architecture school should ideally focus on. My vision for future architecture education is rooted in a balance between historical knowledge and creative thinking, as both are crucial for the discipline.

Phil Thank you both for sharing your experiences, insights, and perspectives – this has been an enriching conversation.

DIALOGUE 4
PHILIPPE BLOCK AND INDY JOHAR
MODERATED BY PHIL AYRES

Phil Philippe, it is now more than three years since your keynote at FABRICATE 2020. In the framing for that presentation, you started off with some very stark quantifications in terms of the demands faced by the construction sector needing to cater for a burgeoning global population, together with the sector's negative environmental impacts in terms of greenhouse gas emissions, resource use, waste production, and energy use. You articulated the need for changing how we design and build, and offered some really tantalising examples, insights, and methods being developed within your research group. In the time since your keynote, and looking broadly across the sector, have you seen positive trends and fast enough transitions? If not, what do you feel are the systemic barriers and impediments to change?

Philippe There has been a lot of change in the last three to four years, especially in the European context. There is a clear call for action and rising expectations in response to the demand that we do things better, while we are acknowledging the direct relation between climate change and the impact of the building industry and built environment. I emphasise Europe, because today, sadly, this is not a global occurrence – there is a different sense of urgency or even acknowledgement in different parts of the world. What we take for granted in Europe, as necessary next steps, is not being carried out at the same speed and with the same level of gravity, globally. Have there been positive trends? Yes, this escalating awareness, but also the installation of incentive mechanisms such as taxes, grants, the European Green Deal, and so on. These are good, but is it going fast enough? Absolutely not. Are there some dynamics that are inhibiting faster progress? Yes… I'll give you an example. In Switzerland, we are just getting past – I hope – a period of concrete shaming, which has already lasted at least two or even three years. The issue for me here was that the entire sustainability discourse was unnuanced and overly simplistic, a discourse that tended to advocate simply that 'wood is good' and 'concrete is bad'. That focus on the message that we need to shift to greener materials to be more sustainable has, in practice, limited truly sustainable development. A more precise perspective shows three primary levers that need to be addressed, in parallel. The first one is indeed the need to reduce the impact of the materials used. Second is to use only the materials and quantities you need – this is where structural design and optimisation come in. Lastly, we need to think of end-of-life and how to keep resources, components, or ideally the building itself, in the loop, so circularity.

I would like to mention that I think industry is reacting with suitable enthusiasm. I have the most expertise in the concrete industry. As a board member for a large material company that uses a lot of concrete, I can confirm firsthand that management teams have developed an aggressive decarbonisation roadmap. I witness a significant, new sustainable innovation being introduced almost every three months. This makes me hopeful; but still, it's not going fast enough.

I've talked about awareness, but it's also about designing and building differently. Here, there is not a lot happening in practice. On the design level, things are super slow because they challenge business models. They challenge liability. They challenge legal frameworks. Additionally, the norms are not fast enough to follow new ideas. In this context, I definitely believe that we need to start thinking outside of the box.

Phil Indy, in your work you refer to these aspects of business models, liability, and legal frameworks as 'dark matters', and your practice operates directly in this arena. I want to pick up on this shortly, but could you first articulate the kinds of shifts that are necessary in the ways that we design, and offer some insight on how architectural fabrication might be leveraged to be a part of this rethinking?

Indy I want to build on what was said by Philippe. I'm not sure we are understanding the scale of what we're facing. If Europe wants to stay within 1.5°C targets, and you look at the available carbon in the system, you can't afford to build 1.5 million homes a year – the figure is closer to 144,000 homes. A typical UK building has 800kg per metre squared of embodied carbon. The best low-carbon house has 150kg of embodied carbon per square metre, but we need to get to 6.3kg. I think the innovation space that we're being sold is non-real, and exactly as Philippe was mentioning, a move to timber doesn't solve anything if you rely on global timber supply chains. In order to move to timber, you're going to have to move towards the bio regional timber base. There is a structural land use transition that's required in many countries to move to a bio-based economy, and that has a 30-year window minimum and will add to the food pressures that we've got. Then, we have to be able to sequester that carbon for 200 years. But, most modern buildings have a lifespan of less than 25 years because they're programme-driven buildings. We need those buildings to survive, but we don't have the material registry frameworks for that materiality to survive for 200 years. We don't have the end-of-life material management liabilities on those frameworks. We don't have the legal governance of those materials. Our asset codes for buildings, in terms of how they're financed by pension funds, are entirely financed on use – they're not financed on the material reuse of those buildings. So, what we have are structural issues that are locking us into a problematic space. This is how I would define where we are, and being radical here, we should not be building in Europe. We have 33% of our buildings lying empty. I think the innovation space is to radically increase the utilisation of our built environments and we're going to have to radically reduce the materiality around development. We have to massively reduce the engineering and talk about smart buildings with smart failure management, which isn't based on huge levels of redundancy in our material fabric.

Philippe This is spot on, and to add to what Indy just said – the biggest gain to be found on the design level is tackling these historically grown redundancies and material wasting. We have to work with the materials that are available at scale and that's why I enjoy demonstrating that concrete done well is, today, the most sustainable solution, exactly because we propose a strategy at scale. We consider end-of-life, recycling, upcycling, or full reuse of components. Stopping construction is not a reality that is going to happen.

Phil I'm going to pick up on your comment earlier, Philippe, where you were raising some of the key levers around materials impact and optimisation. Another lever is material diversification, and there are works from your research lab that I find particularly inspiring because they really engage with this area – for example, using panel products made from recycled milk cartons or mycelium-based composites. The conceptual frameworks through which you operationalise this diversification appear to be less about the application of advanced technology and more about the application of transferable structural knowledge. Can you elaborate a bit on this?

'I THINK THE INNOVATION SPACE THAT WE'RE BEING SOLD IS NON-REAL … A MOVE TO TIMBER DOESN'T SOLVE ANYTHING IF YOU RELY ON GLOBAL TIMBER SUPPLY CHAINS.' INDY JOHAR

Philippe Thanks for that question. This not only connects to what I was trying to say before, but it's been our mission to clarify how strength through geometry and more specifically how masonry logic provides an opportunity for fully circular design. Let me expand on that a bit. Historical masonry structures, beautiful Gothic cathedrals in stone, for example, were designed to work with a material that is happy in compression – they get their stability because of their correct geometry, without needing mechanical connections, steel reinforcement, or glue. Materials are kept separate. Because one had thick, generous sections, with the structure aligned to the forces, one had a delicate, equal distribution of stresses, resulting in very low stresses in the system; such structures are therefore not designed for peak stresses as in bending structures. These aspects and principles of traditional masonry construction offer tremendous opportunities for circularity: you reduce by placing material only where needed; you activate low-strength, low-carbon-footprint materials; you have a system that is dry assembled and that can be taken apart; and, because materials are kept separate, you can easily recycle, if reuse is not possible. So you have a natural approach to reusing components and keeping resources in the loop.

To connect to the second part of your question, many new low-emission materials can take an appreciable amount in compression but are not too happy in bending or tension, so this structural masonry logic allows them to be used safely. It allows for the activation of waste materials that otherwise are discarded as non-structural infill. In this manner, new material solutions based on, for example, waste streams can be made perfectly structural.

But we always act on two levels. On the one hand, as our industry needs impact today, we work with low-strength, green concretes in which the high-carbon-intensive clinker in the cement is replaced by industrial waste products, calcined clay, recycled construction demolition waste, and so on. We have dedicated a lot of effort to proper experimental campaigns, with results now moving to building sites – delivering floor plates that work in a real-life context in which certifications and building norms have to be satisfied. These floors are cutting 85% of greenhouse gas emissions compared to your typical flat slab in reinforced concrete.

On the other hand, I also find it important to look at alternative materials that have another horizon, perhaps becoming accepted in five to ten years, or even later, such as 3D-printed marble waste using a geopolymer binder or grown mycelium. But what they all have in common, and that's why I like that you asked about 'transferable structural knowledge', is that they are all perfectly congenial to this masonry logic. I like to conduct research at these two speeds. But to your point, I think we have found, and are increasingly demonstrating, a structural typology that advances the applicability and design space of low-strength, low-carbon-footprint materials.

Phil Indy, scarcity of conventional resources is an externality that is bearing heavily upon us. Another one is the precarity of global supply chains. We're seeing renewed efforts at many levels to determine and assess local resource assets, some of which exist with prior traditions, and some of which are novel. What effects do you feel this will have on the way that we fabricate – and do you already see the emergence of a more distributed, localised, and heterogeneous production landscape?

Indy I think so, but let me build a little bit on what was said. What we have to understand is that energy is a key function of what's driving our material economy. Now if we look at a 30-year cycle, and we say that in the next 10 to 15 years we have moved from hydrocarbon energy to, probably, micro nuclear as an intermediary energy source, we can have a new thesis of intermediary abundance. That energy abundance will open up different pathways. So, for example, it might be more sustainable to use textiles. I think external pressurised textile skins, especially if we can get them to be bio and recyclable, will become a salient part of a building skin technology landscape, and we will be able to do structural work using this. I think that's all dependent not only on building a biomaterial economy, but on the nature of our energy supply: whether we have renewable energy resources, and how we're moving from one to the other.

So, I just want to show in this conversation the linkages of these decisions and what we're facing is a turbulent frame in the transition from one to the other. And as we move from one to the other, as you rightly point out, we're going to have to re-organise supply chains. And this is not simple. We're going to have to rebuild some of those biomaterial bioregional land bases in order to do that. And then what we're looking at is how do you finance circular business chains? How do you own the liability of a piece of timber across its full lifecycle? But that then uncovers some critical governance questions about not creating new rent-seeking frameworks. So how do you deal with governance models around these new circulars, and how do we make sure they're really transparent? What do the frameworks look like? So, I just want to show the kind of richness of the conversation that we need to be in the middle of, both in terms of the energy transitions we face and the material choices that we make.

My intuition right now is that these things are dynamic, but they're going to require some hard decisions. The prevailing European policy to retrofit our housing across Europe implicates a quarter of a billion homes. We don't have the labelled supply. We don't have the mineral resources to be able to do that, so we're facing not only material constraints, but new labour constraints that operate in an aging population. I think it's going to be extremely difficult to import labour, but if we don't do that, then we're going to have to make choices about where we deploy European human labour into the system. And the question really becomes, do you want to employ large parts of the European population to retrofit our houses, or do you want to deploy the European population somewhere else? I think these are substantial questions, and I suppose my worry is that – and I really appreciate Philippe's detail on this – much of industry is participating in simplistic conversations and making simplistic decisions: 'timber is good, X is bad'. When you actually look at the details of it, it's a highly nuanced problem space, and I don't think we're giving ourselves time to be nuanced.

I also think our global supply chains will face additional shocks. I mean, last year, you saw India ban exports of rice. We are going to see global supply chains increasingly becoming non-commodity geopolitical devices. What does that do to our inflation risks? We're seeing large percentages of inflation in material economies. What does that do to the cost of construction? We've seen massive increases in the cost of construction already, so I think we're going to see a natural dampening of the construction sector, driven not by demand, but by all the other systemic volatility on the table. I think that's going to require us to readjust how we live, what we think high-quality life looks like – the amount of space per person that we've become used to. Transformation is required, and while it does provide space for new business models, it also presents new governance challenges.

Phil I'd like to shift the conversation towards the role of technology – specifically digital fabrication and automation – in the necessary transitions that have been outlined. There are clearly value propositions that can be made about the use of these technologies, but it can also be argued that they are a product and ultimately dependent on many of the extractive, linear, and capital concentrating systems that we need to reconsider. Can these positions be reconciled?

Indy So, again, I think nuance is everything here, Phil. If you're looking at retrofit, it's very difficult to do in terms of re-skinning buildings, given the diversity of building stock. If you look at the production of solar panels, or battery production, or whether you look at ice or heat pumps, yes, you could automate some of their production radically, and that would have quite a lot of value. That's probably the most efficient automation cycle investment that we could do now, whereas doing deep retrofit automation is probably not an efficient allocation right now just in terms of the complexity that's required on the ground. So, the question is, where does automation work effectively?

'IT'S ONLY WHEN WE HAVE A REASONED DEBATE AT THE INTERSECTION OF THESE PROBLEM SPACES THAT WE GET TO THE RIGHT SOLUTION SPACES, BUT WHAT WE'RE CURRENTLY GETTING IS SILOED RESPONSES.' INDY JOHAR

There's a philosophical question that you're asking in the back end of that, which is the nature of our technologies and the nature of rent seeking and power asymmetries buried in those technologies. Most of our technological frameworks are built on theories of extraction, and they're all about the accumulation of asset value rather than development value of human beings. So, there's a macroeconomic question that I think we are going to have to address. What do life-affirming technologies look like? How do we radically start to shift our material economic base towards them? What are the funding mechanisms to be able to support them? We also need to be acutely aware of the embodied carbon and the embodied energy costs of many of these technologies, as we have lost the headroom for many of the carbon investments needed to make those transitions. We are in borrowed space, operating in these extraordinarily tight limits in ways that I don't think we're being quite real about.

Philippe To add to this, buildings in different contexts have different requirements; so I don't think we can make blanket statements here. What I see as a particular challenge is the perspective that many architects have, that every building is a prototype, that every building is a one-off. We need to get past such an attitude, and we need to find practices that allow us to make significant improvements towards efficiency, productivity, and so on, through standardisation and modularity. Automation can be part of the solution, but what is clearly hindering this is the attitude of the 'one-off'; I consider it a fundamental reason why we stay in this never-ending loop of inefficiencies. We are not learning from our past experiences and thus also not tailoring to an economy that can be more circular, which would be enabled through agreement on meaningful grid spans, unit length, façade modules, and more.

Another aspect is that there often seems to be a fascination with certain technologies without clearly knowing exactly what we're trying to do with it. One example that boggles my mind is how so many people are really convinced that large-scale, on-site 3D printing is going to solve everything. The only argument they have so far is – maybe – productivity: delivering faster. Instead, what we are producing with all this investment are buildings made by squirting a material in one go, resulting in a monolithic 'blob', which we do not know how we will maintain, let alone how to take apart. Additionally, we have to do all kinds of chemistry magic to make these things happen. I am not even talking about the energy, logistics, and scalability questions that seem far from solved or even solvable in a meaningful way. I think it comes back to this non-nuanced way of talking about sustainability and what we can achieve. Maybe that's a bit harsh for all these researchers working in this field, but I just want to nudge them to at least be clearer about exactly what we are achieving through the introduction of such technologies in our constructed environment.

Indy I want to build on the point of efficiency. There is another critical way of looking at this problem: for most corporations, real estate is less than 6% of its cost, if not less, whereas around 60% of its cost is employees. We know that elevated indoor CO_2 levels can reduce cognitive function by up to 10%. So, I think we need to radically shift the quality of outcomes provided by built environments and their effect on human capabilities and human cognition. I don't think we're anywhere close to what I would consider appropriate standards. As much as I'm interested in the efficiency of buildings, right now I'm radically more interested in the outcome quality of built environments and their impact on human value at a much deeper level, as most of our built environment is really slum in terms of these micro balances on the human body.

Phil This segues into questions about new partnerships and collaborative frameworks that need to be developed. Could you offer your thoughts, and outline some of the prospects they hold for reshaping the world of fabrication?

Indy First, we need to recognise that the scale of the transition we face exists at the intersection of these problems, and if we only focus on one of them, what we end up with is that we mis-optimise the system. So, we need to recognise that we do have carbon constraints; we do need new material economies; we do need to radically shift human comfort expectations; we do need to improve built environment quality from a human health perspective – and at the intersection of that is a new built environment economy. It's only when we have a reasoned debate at the intersection of these problem spaces that we get to the right solution spaces; but what we're currently getting is siloed responses. You've got regulation doing one thing, not recognising technical limits, and on the other side, technical limits not recognising some of the climate change numbers that we're facing. So, I think you have to look at the problem through an intersectional lens. We are going to have to multi-solve and move away from segmented responses. I think it is really important to recognise that it is not an options conversation – it's an intersectional conversation.

From there, the people who are able to innovate are the vertically integrated owners of systems. People that have access to the supply chains, people that have access to land in a longitudinal value sense. Those longitudinal holders of liabilities and supply chains can, right now, move outside the prevailing market conditions and start to look at what future market conditions can be.

Philippe Owners and developers are starting to see value in the end-of-life, or the next life, of their buildings instead of just writing them off. So maybe approaches like 'materials as service' might incentivise companies to make sure that the value of and in our buildings is maintained and that resources can be recuperated. But there are much more banal and immediate things we can start to tackle today. In Switzerland, practically each (larger) project goes through an architecture competition, and that means, because of the open tendering phase later in the project, you're not allowed to collaborate with a contractor. And if you do, then that contractor is excluded from bidding on the project because they have advanced knowledge and a conflict of interest. I wanted to address this because it is an example of how established practices today can impede creating a closer link between design and construction. For the introduction of innovations in construction through, say, biofabrication, I strongly believe that this fabrication and construction knowledge needs to be integrated in the design process from the very beginning. There is a lot to be done in this space, but we are far away from that, and that's why we need to move very, very fast.

Phil Thank you both for sharing your insights and perspectives. This has been an enlightening conversation.

'OWNERS AND DEVELOPERS ARE STARTING TO SEE VALUE IN THE END-OF-LIFE, OR THE NEXT LIFE, OF THEIR BUILDINGS INSTEAD OF JUST WRITING THEM OFF.' PHILIPPE BLOCK

LOCALISE
RECLAIM
INTEGRATE
RATIONALISE

3 INTEGRATE

SYSTEMS AND CONTEXT

HOUSE OF CORES

LESLIE LOK / SASA ZIVKOVIC
CORNELL UNIVERSITY
FABIAN MEYER-BRÖTZ
PERI 3D CONSTRUCTION GMBH
HIKMAT ZERBE
CIVE

Introduction, state of the art, and context

Deep collaboration between industry, practice, and academia is needed to comprehensively respond to global resource challenges and to co-develop new, integrated, applied, and resource-efficient models for construction. *House of Cores*, expected to complete construction in 2024, is the first fully permitted two-storey 3D-printed home in the US (Fig. 1). The research project is the result of a multi-year collaboration between HANNAH, PERI 3D Construction, and CIVE, as well as several building industry partners. *House of Cores* is designed as a hybrid material structure of concrete and timber framing, establishing a flexible construction system that can be readily adapted to multi-family housing in the US. The project expands on prior work by the collaborators such as: (1) PERI's 3D Printed House in Beckum (Weger *et al.*, 2021), which was the first printed house in Germany, a two-storey concrete structure with 3D-printed loadbearing walls, half-slab flooring, and a system of steel-reinforced semi-precast concrete elements; (2) HANNAH's Ashen Cabin (Lok and Zivkovic, 2020), an experimental building that synthesises a 3D-printed substructure with a robotically fabricated wood envelope; and (3) research projects such as Additive Architectural Elements (Zivkovic and Lok, 2018), RRRolling Stones (Zivkovic and Lok, 2021), and the first 3D-printed apartment building in Germany (PERI, 2020).

The 375m² *House of Cores* illustrates the possibilities of in-situ 3D construction printing technology, mass customisation, and design solutions that integrate conventional construction methods. The project is printed using the COBOD BOD2 gantry printer and takes advantage of the printer's modularity for its programmatic residential layout on an urban plot (Fig. 2). The project serves as an active testing ground for (1) 3D print process and logistics optimisation, (2) material sustainability evolution including a transformation from mortar printing to concrete printing with aggregates, (3) innovations in design and mass customisation, (4) a mix of on-site and off-site 3D-printed construction, (5) structural innovations in relation to printing logistics and the integration of wood framing through critical details, (6) the integration of various associated trades, and (7) permits and on-site inspection schedules. In this process, the project establishes a logistical and design ecosystem for 3D-printed construction that exhibits many successes and scores of productive failures, highlighting that radical

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technology application in the AEC industries requires embracing an ethos of collaborative continuous learning.

Architectural design, building integration, construction logistics, and sequencing

House of Cores illustrates the possibilities and challenges of in-situ 3D construction printing technology, mass customisation, and design solutions that integrate conventional construction methods. The building's main spatial organising principle establishes a series of 3D-printed load-bearing cores that contain functional spaces, bathrooms, storage, and stairs. While largely printed in-situ, the project also includes large-scale prefabricated elements that were printed on the floor slab and were later installed with a mobile crane to form a four-storey, 12.8m-tall chimney (Fig. 3).

The printed walls are insulated using a new closed-cell foam insulation system with a significant recycling content by Huntsman Building Solutions (Fig. 4), working in synthesis with a highly efficient variable refrigerant flow (VRF) HVAC system by Toshiba Carrier to regulate interior temperature and air moisture content. The five primary structural 3D-printed cores in *House of Cores* are connected by lightweight wood framing for floor, ceiling, and non-loadbearing wall assemblies (Fig. 9), generating an architectural and spatial alternation of concrete and wood-framed walls with glazed infill, and a mix of light and heavy materials. On the exterior, this alternation is expressed by the contrast between the vertical lines of the metallic standing-seam cladding and the horizontal 3D-printed concrete layer materiality (Fig. 5). On the interior, the project highlights the design potential of mass-customised architectural components to meet the homeowner's programmatic needs: layers of softly undulating concrete reveal customised storage spaces, lighting, bookshelves, and display shelves for the building's users (Fig. 6).

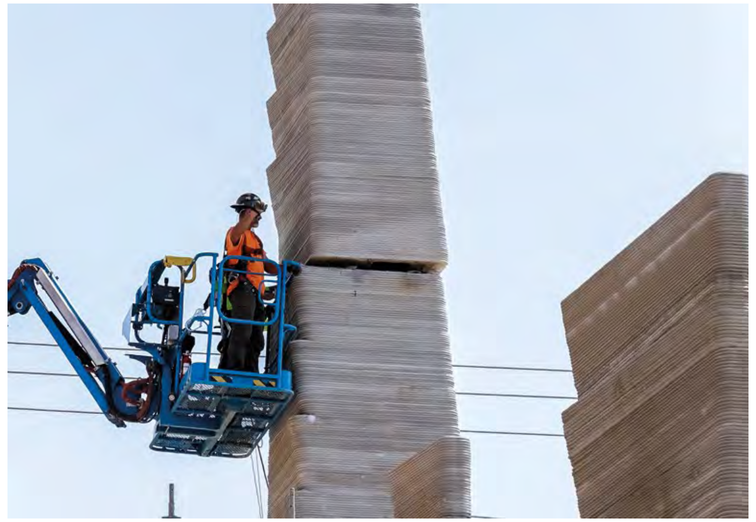
Permit drawings, including a full set of architectural and structural details, were submitted to the City of Houston in November 2021 and the building permit was granted in April 2022. A number of custom procedures for on-site inspections were developed in collaboration with the building inspectors, especially pertaining to structural inspections prior to grouting the embedded rebar as well as upon the installation of embedded electrical boxes and conduits. The latter required close coordination with the electrical contractor, making sure that qualified personnel are on site to install the electrical boxes during the printing process. The two-storey configuration of the project necessitated multiple installation visits, for outlets at 450mm and 1220mm high, as well as for the conduit installation, before the final grouting of each storey. The project's printing sequence in three sections (see elaboration on the printing process below) further complicated the scheduling of different trades and inspections, leading to a number of delays in the overall printing process. The complex electrical conduit layout within the printed walls required a series of special drawings, which were shared with the electrical contractor via a mobile phone version of Rhino 3D, simplifying the complex communication of conduit geometries. The building utilises two types of insulation: a closed-cell spray foam for the 3D-printed concrete walls and an open-cell spray foam for the timber-framed exterior walls. Similarly, the installation of the spray foam insulation was divided into four visits, coordinated with the progress of the 3D printing. The cavity was designed to accommodate a maximum height of 3m, ensuring that the slow-rising spray foam could expand effectively. This height requirement was essential for sequencing the spray foam installation with the printing completion of the first and second floors. The open-cell spray foam will be completed in one visit when the exterior framed walls are completed.

3D-printing process and technology innovation

PERI employed the COBOD BOD2 printer for printing the *House of Cores*. The building was printed in a total of three sections. The first section contains one of the cores printed as well as the adjacent chimney (Fig. 7). While the bottom 6.7m of the chimney structure was printed in-situ, the top 6m was printed as two 3m-tall prefab elements.

1. In the printing of the first section, the southern core features an interior staircase and an integrated bookshelf that faces the living space. © Anthony Vu.

2. Aerial view of the printed structures on site, showing the five cores and the lifting of the 3D-printed prefab chimney components in place. © Brian Austin.



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3. Installation of the second prefab chimney component by a mobile crane to form a 12.8m-tall chimney. © Brian Austin.

4. Injecting closed-cell spray foam insulation in printed cavity to create an airtight, vapour-tight, and well-insulated building envelope. © Anthony Vu.

5. Rendering of the east elevation showcasing the alternation of the vertical standing-seam cladding and the horizontal concrete layers. © HANNAH Office, Houston.

6. Detail of toolpath undulations of custom shelving at the entrance space. © Anthony Vu.

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The second and third sections consisted of two cores each. The team took advantage of the modularity of the BOD2 by setting up a smaller four-legged configuration for the first section (southern wall), and a larger six-legged configuration for sections 2 (middle walls) and 3 (northern walls). The printer was fed with a continuous mixing pump – the SMP III Connect model from the manufacturer mtec – which was mounted underneath a custom-made 4m^3 silo. The silo was filled using 1m^3 supersacks with a telescopic handler. During the printing process, a multitude of smaller issues were identified, analysed, and improved upon.

(1) The environmental conditions of the Texan heat in summer: A water chiller was installed in order to control the temperature of the mixing water, maintaining a range of 2.7°C to 24.0°C, in order to optimise the balance between the material's chemical reaction time and adequate yield stress at the point of extrusion using an approximately 30m-long hose of size DN50.

(2) Crack avoidance: Directly after stopping the printing process, the printed structure was covered with Sika UltraCure™ blankets. Additionally, expansion joints were included for walls longer than 3m. Even with the water chiller and these additional curing methods in place, cracks formed in certain printed layers during longer layer times and hot days. To address this issue, a fibre mesh was affixed with epoxy to the layer where cracks had developed. This effectively restricted further propagation, and any residual minor cracks were easily filled with QUIKRETE® Crack Repair once the material had fully cured.

(3) Printing at greater heights: When printing the second storey with high print speeds and tight curves, the BOD2 printer exhibited some instabilities, leading to shaking. To mitigate this, the print speed had to be decreased from 250mm/s to 200mm/s.

(4) Sensors and cameras: Achieving mixing consistency when incorporating changing hose lengths and varying environmental conditions has proven challenging throughout the project. For better control, a water flowrate sensor from the company IFM was deployed to allow for digital measurement and control of the added water in the continuous mixing pump. Additionally, cameras in the mixing chamber as well as in the hopper of the printer allowed the operator to continuously visually monitor material consistency.

(5) Scaffolding: To ensure workers' safety, scaffolding was erected alongside the printed structures for work at heights (Fig. 8). Construction workers, instead of print operators, were responsible for assembling the scaffolding. Consequently, the positioning does not always accommodate the printhead's required manoeuvring space. Adjustments to the scaffolding had to be made multiple times during the project. Based on this experience, the team recommends integrating a complete virtual model of the scaffolding into the printed geometry model to streamline such projects in the future.

7. Aerial view of section 1 printing in progress with COBOD BOD2's 4-legged configuration. © Anthony Vu.

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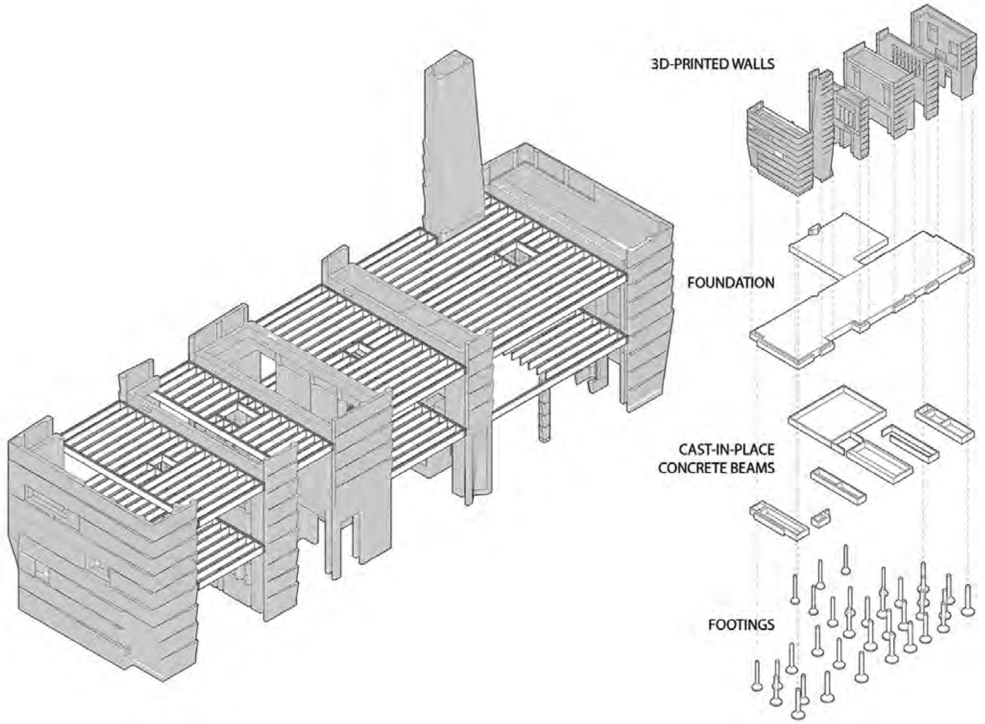

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8. View from the kitchen towards the two-storey printed bookshelf in the living room. Scaffolding is erected around the printed cores for the second-storey printing. © Anthony Vu.

9. Axonometric drawing illustrating the integration of the five printed cores, wood framing, foundation footings, cast-in-place grade beams, and slab. © HANNAH Office, Houston.

Integrating these as well as other learnings led to an increase in productivity by a factor of almost two over the course of the project. In December, an average of 12.9t of material was printed each week, while in May and June an average of 21.5t was printed each week.

Structural system innovations

The structure consisted of a load-bearing wall system for the vertical elements and conventional wood studs and trusses for the floor and roof slabs. The bearing walls were supported on a cast-in-place reinforced concrete slab-on-grade with grade beams spanning beneath all the printed wall. Additionally, 3.6m-deep bell-bottom piers with pier-caps are integrated with the grade beams and placed at appropriate locations to ensure proper transfer of all loads into the underlying soil layer.

The bearing wall system consisted of five structurally independent 3D-printed cores. Although the applied loads, which consisted of Dead Loads, Live Loads, and 214km/hr Wind, generated small stresses in the bearing walls, an integrated structural system that provides continuity between the two floors and the foundations was necessary. The bearing walls were checked for compressive stresses due to gravity loads, and for shear stresses due to the wind loads using the stress limits provided in Chapter 14 of ACI-318 (n.d.) (Plain Concrete), using a concrete compressive strength of 35MPa. In all load combinations, the Demand to Supply ratios were extremely low because of the large areas of printed concrete. No flexural verifications were conducted, as the substantial self-weight of the structure effectively counterbalance any uplift forces generated by potential overturning moments.

Thus, the main concern, of being able to provide continuity in the system, and eliminating all possible slenderness issues in the walls, was achieved in each of the five cores by careful planning of the wall configuration. The wall configuration, as shown in the wall sections, varied between exterior walls and interior walls. The exterior walls were made of double-shell walls with a gap in between that was filled with spray foam insulation. The outer shell was made of two adjacent runs of printed

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concrete, generating a solid wall 150mm thick. Vertical ribs were created in the inner run at 1.5m spacing, generating cavities, and were reinforced with a ϕ16 rebar spliced with a dowel chemically anchored within the foundation. These ribs were later grouted to form bond columns.

The inner shell of the exterior walls and the interior walls consisted of two runs of printed concrete that were adjacent for the lower part of the wall. These two runs were separated with variable distances at the top part of the wall for architectural purposes, creating a void volume. Longitudinal and transverse rebars were placed (Fig. 10), and later grouted to generate continuous bond beams at each floor for each of the five printed cores. The outer shell and the inner shell of the exterior walls were interconnected, with inverted U-shape rebars placed at appropriate locations, and all walls had temperature and shrinkage reinforcement placed horizontally between printed layers.

Additional bond columns were created at the corners of each wall, thus generating a full structural system made of the bearing walls with continuous bond columns running the entire height of the structure and continuous bond beams at both slab levels. This ensured stability within the two-floor system and generated an integrated and independent structural system for each of the five printed cores.

The floor slabs selected with this system consisted of wooden trusses and studs that facilitated all the HVAC requirements. They were connected, using face-mount hangers, to double ledgers fixed with the concrete walls using chemically anchored threaded rods. This simple yet versatile system has no diaphragm action to connect the five cores; thus, it was designed and detailed for gravity loads only.

Concrete sustainability and conclusion

The *House of Cores* represents a step towards more sustainable construction with concrete in several ways. First, the wall assembly in the concrete cores ensures no thermal bridging between outer and inner printed layers. The printed façade is anchored to the inner printed layers with conventional wall anchors known from double-shell masonry structures. This results in a thermally efficient building envelope with a cavity for closed-cell spray foam insulation, which can be flexibly adjusted to meet or exceed building code requirements (Fig. 11). Second, in the course of the project, the 3D printing material was reformulated and optimised. Most noteworthy, the maximum aggregate size used in the material formulation was increased from 4.8mm to 9.5mm (moving from mortar to concrete printing), where the latter will be used for printing the detached garage. This has also led to a reduction of the global warming potential from 406.6kgCO_2e to 360kgCO_2e. Third, the use of concrete was limited to the load-bearing structures only, ensuring a mindful consideration of the sustainability impact.

10. On-site construction progress showing rebar insertion during the printing of the exterior wall. © Anthony Vu.

11. Views of the east-facing façade as double-shell masonry structures with closed-cell spray foam installation sandwiched between the outer and inner printed layers. © PERI 3D Construction.

Printing the *House of Cores* as a residential home for conventional use has proven challenging. The project site has been freely accessible during the whole period of printing and hundreds of visitors as well as various media entities have been welcomed to transparently share the knowledge gained and lessons learned in an open-source approach.

Many minor complications, particularly the effective integration of various trades within residential construction, at present hinder the construction industry from fully embracing digital fabrication for substantial gains in impact, sustainability, and efficiency. To induce change on a global scale and take full advantage of automation, transitional resource-efficient models must place a central emphasis on existing labour resources, multi-material approaches, and affordability. This project's principal contributions involve addressing these barriers and calls for greater emphasis within the broader academic community on applied, holistic building processes in the realm of residential construction.

Strategically combining the advantages of concrete 3D printing with wood framing, *House of Cores* aims to increase the applicability of 3D printing in the US, where framing is one of the most common construction techniques. This transitional future of fabrication combines tradition and innovation, adapts sensibly to various contexts, and acknowledges that *incremental steps* must be taken to advance our construction practices within a resource-challenged world. Altogether, the varied design strategies featured in *House of Cores* aim to move the needle towards increased impact, applicability, sustainability, and cost efficiency of 3D printing for future residential and multi-family buildings.

Acknowledgements

A new generation of specially formulated 3D-printable concrete for this project is supplied by QUIKRETE.

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Structural connectors for this project are supplied by Simpson Strong-Tie.

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3D-PRINTED EARTH ARCHITECTURE
DESIGN APPROACH FOR A PERFORMATIVE HABITAT

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Introduction and context

Digital transformation and green transition
As the European Commission (EC) states, *'Climate change and environmental degradation are an existential threat to the world'* (EC, 2019). Therefore, our resource consumption, technology usage, and social lifestyles are called into question. Translating this into the creative industry implies a need for new sustainable practices while maintaining economic and cultural inclusivity in accordance with societal needs, as outlined by the recent initiative 'New European Bauhaus' (EC, 2020). In the architecture, engineering and construction (AEC) industry, similar requests are made in the search for design and technological solutions that might reduce the impact of our building on the environment (EC, 2018). In response, there is a vital need for this sector to innovate, design, and construct with a holistic understanding of the consequences of each decision.

Earth construction: Knowledge and challenges
Earth construction methods, based on ancestral techniques that take advantage of local materials, are today a viable alternative to the contemporary challenges of energy efficiency (Minke, 2014). Their close to zero ecological footprint is a great advantage for the industry leap to meet prevailing energy consumption and emission goals.

Almost any mineral ground that contains clay can be used for construction (Moevus *et al.*,2015). At all stages of its use, earth requires little embodied energy – for example, no firing energy and minimal processing (Christoforou *et al.*, 2016). Earth is easy to maintain and repair, can be recycled, and does not generate waste. On the contrary, excavation 'waste' from other construction sites can be used to make new building materials (De Cooman, 2020). Thanks to their thermal inertia, earth construction methods allow for substantial savings in the cost of energy during winter and summer as a result of their naturally embedded capacities for heating and cooling.

Finally, the natural ability to absorb and evaporate means that earth constructions are able to regulate humidity, promoting a healthy indoor climate. Although earth as a construction material is freely and abundantly available, traditional earth-building techniques require labour-intensive processes that cannot compete with contemporary materials in terms of cost, quality, and performance (Heringer *et al.*, 2022).

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1. The completed 3D-printed house project TOVA, realised in collaboration by the Institute for Advanced Architecture of Catalonia and WASP. © Gregori Civera.

Opportunities raised by AM and computational design
Additive manufacturing (AM) is continuously gaining momentum in the construction industry, offering the opportunity for newer applications in large-scale printing. While the potential of this technology is clear for AEC, its democratisation in the industry remains at an early stage. The advancements of CAD have already led to the design of complex and optimised building geometries, and AM is enabling advanced material fabrication and distribution processes, setting the ground for more efficient buildings. AM has the potential to precisely create complex geometries that were previously too expensive to construct, while permitting a drastic reduction of production waste (Barbosa *et al.*, 2017).

On the other hand, computational design processes have opened new opportunities for architecture, with better control of complex geometries via an integrated design workflow, from which a new architectural culture has emerged (Picon, 2010). In particular, researchers at the intersection of computational design and digital fabrication explore the interaction between geometry, fabrication, and performance (Glynn and Sheil, 2011), offering the possibility for a new design approach integrating feedback from the material and fabrication processes (Oxman, 2007).

3D printing earth opportunities and challenges
AM with earth has the potential to recover this traditional material within our contemporary cultures, and to simultaneously answer the prevailing exigencies of quality, cost, and efficiency. The technology has lately been introduced in the construction industry, with examples of AM with earth materials, such as clay and mud, already existing in the literature. Contour Crafting, one of the first research projects exploring 3D printing at construction scale using a concrete mixture, encompassed applications for earth material 3D printing (Kwon, 2002). From 2010 onwards, experimentation in printing at a large scale has expanded, with the research led by the Institute for Advanced Architecture of Catalonia (IAAC) (Giannakopoulos *et al.*, 2014), WASP Company (Moretti *et al.*, 2016), and Emerging Object (Fratello and Rael, 2020).

While 3D printing with this material proves to be feasible, researchers are confronted with the complication associated with how to combine this natural material within industrial machinery and digital design processes. IAAC´s approach focuses on adapting machines and design for the construction material, to obtain an enhanced autonomous construction process. In this regard, IAAC targets a higher level of automation than the Emerging Objects semi-autonomous process, and targets a more sustainable earth mix than WASP material, which is reinforced with lime.

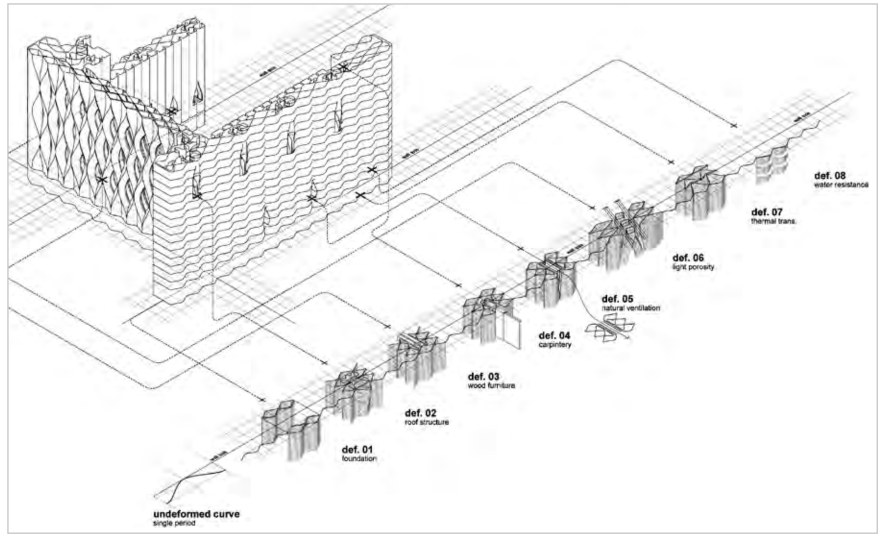
Aim

Using a 3D-printed earth housing unit prototype as a case study, this paper discusses the learnings from IAAC research in 3D printing with earth, presenting a digital design methodology that integrates fabrication constraints, building performance, climatic response, and architectural attributes for a coherent building design. Literature exists on the design approach for 3D printing with clay (or earth), including technical approaches to the robotic process (Kontovourkis and Tryfonos, 2020) and performative approaches to architectural design (Taher *et al.*, 2023). Also covered, in addition to these two, is the semi-structural reinforcement of the double-layer wall adaptive approach to the material challenges (Rael and San Fratello, 2017), which produces a simple interior and exterior expressiveness without any environmental, structural performance, or thermal behaviour concerns. The approach proposed here seems original in creating a workflow that permits the simultaneous integration of robotics, material, and architecture performances into a design methodology that uses a set of simple input curves as a design generator of the full printing path.

Research approach

Learning by doing
The design methodology described in this paper has been developed over the past ten years of research at IAAC, an education and research centre that explores the potential of using technology for creating sustainable architecture. The design methodology has been tested and fine-tuned by researchers, faculty, students, and practitioners over a range of professional and educational projects, especially within the postgraduate programme 3D Printing in Architecture, 3DPA (Cabay *et al.*, 2018). The IAAC's 'learning by doing' approach (Dubor *et al.*, 2019) has proven to be key in integrating the potential and limit of material and machine in the design process, especially when dealing with a delicate fabrication process such as 3D printing using earth.

Combining rapid prototyping and digital simulations
Using prototyping as a validation method across the design process has allowed the integration of material feedback at all stages of the design process. While 3D printing permits rapid prototyping, the use of digital simulations coupled with a rigorous digital design methodology has permitted an expansion of the number of tests and validations that can occur within the design process of a project. This approach, first outlined in the paper 'Energy efficient design for 3D printed earth architecture' (Dubor *et al.*, 2017), is here updated with the latest findings, using the TOVA project as the case study. As detailed below, the TOVA project was developed with the faculty, researchers, and students from the 3DPA edition 2021-2022 at IAAC.



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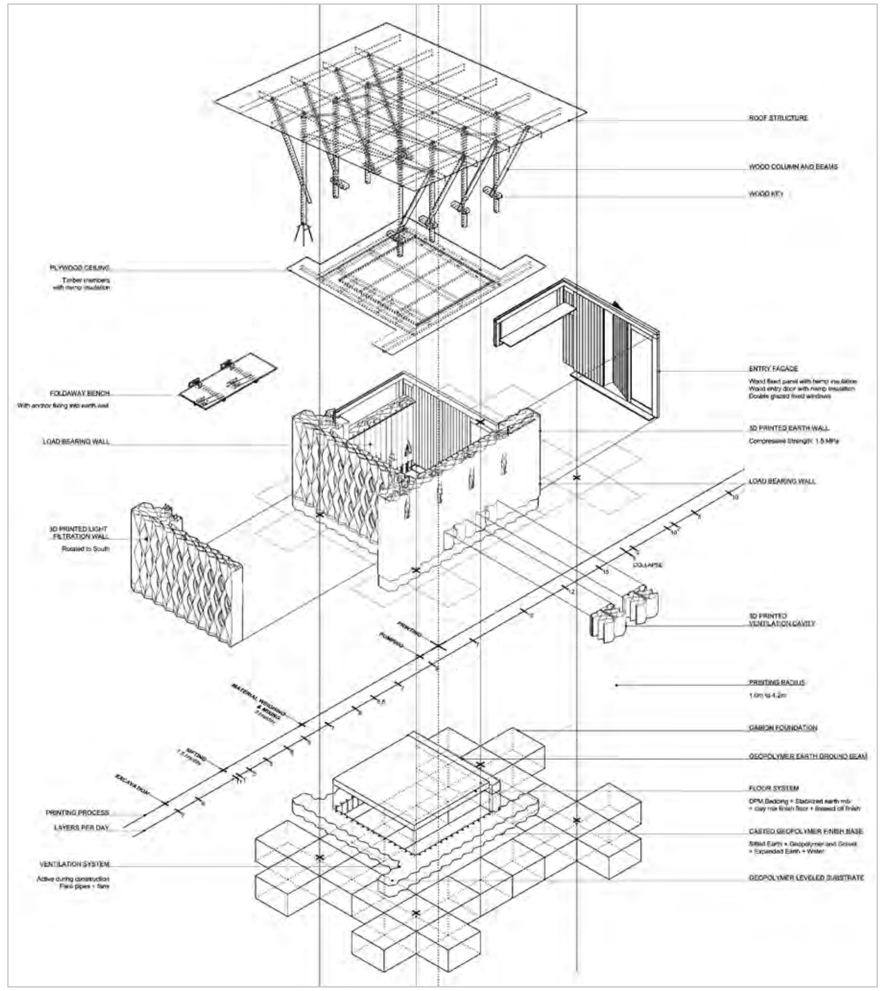
2. Integration of all the details into the final 3D-printed piece. © Institute for Advanced Architecture of Catalonia.



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3. Axonometry of the entire TOVA project. © 3DPA 2021-2022, Institute for Advanced Architecture of Catalonia, WASP.

Design approach

Micro scale: Material and machine behaviour translated into design logics
The design approach chosen at IAAC revolves around lines, and in particular Bezier curves, that can be used both to represent space and to provide precise instructions for material deposition by the machine. The mathematically defined curve, characterised by tangencies, enables exceptionally precise design and smoother fabrication arising from the inherent speed and acceleration transitions created by these formulations. Previous research (Dubor *et al.*, 2019) has shown that design decisions are constrained by the intrinsic behaviours of a natural material such as earth, in particular its low tensile strength and high shrinkage tendency, which can lead to buckling during printing or cracks during drying. To counter these issues, the design approach uses a set of digital simulations, paired with fast prototyping, physical tests, and sensors, that together ensure that the digital design is feasible for building with a distinct earth material, which can vary depending on its geographical location. This approach at the intersection between digital freedom and physical reality enables the integration of other building physics into the design process. Factors such as structural performance, thermal behaviour, light and visibility control, ventilation patterns, and water flows can be incorporated. This innovative approach unlocks new performances previously unseen in earthen architectures.

Macro scale: Fragments and architecture transforming design logics into architectural performance
When scaling up to entire buildings, performative approaches become secondary design parameters, prioritising architectural intention and space syntax. Performance goals are defined as vectorial objects (either a curve or an arrow), while architectural spaces are defined with line axes, both serving as inputs in a generative algorithm that condenses and produces the final geometry, considering the constraints of earth 3D printing. This versatile approach allows for designs with optimal performance while adapting to local resources, climate, and culture.

Case study: TOVA

This design methodology was tested within the TOVA project, a small 3D-printed earth house prototype demonstrator located in the forest of Collserola near Barcelona, and produced by the students and faculty of the 3DPA programme. The goal of the project is to demonstrate the capacity of earth 3D printing to create the smallest possible enclosed space that includes all the requirements and details of a house. The site has a Mediterranean climate (Köppen climate classification) characterised by mild, relatively wet winters and hot, relatively dry summers. The site provides local access to wood and earth for the construction. Inspired by the Mediterranean architectural culture of spaciousness, and the principle of earth architecture, the building is covered by a broad shading roof that protects it from sun and rain.

The 3D-printed wall, including its details and performance, is described by a set of digital curves, which deform at any location where an architectural, structural, or climatic detail is needed. The first step of the design is the definition of a generic pattern, made from the smallest repeatable curve segment – the period – and arrayed longitudinally so as to create the drawing of a wall. Wherever needed for performative purposes, this generic pattern is modified to fulfil a precise function.

TOVA contains eight different deformations from the original pattern for the following features or performances: (1) wall base, (2) roof structure, (3) integrated furniture, (4) carpentry details, (5) ventilation, (6) thermal transmittance, (7) light, and 8) water protection.

The first 30cm and lower part of the building walls, which have higher water-resistant requirements because of their inherent environmental vulnerability, was produced with a different manufacturing strategy. A lost 3D-printed formwork was executed following the same curvilinear pattern as the rest of the building. This was later filled up with a material mixture with better water-resistant capabilities than the rest of the building, creating a sturdy base (1), which acted as a foundation reinforcement. Extensive research was conducted on both the poured material (an earth + geopolymer mix) capable of resisting water erosion, and the formwork geometry (earth 3D printed) capable of resisting lateral pressure of the poured mix when liquid.

The structure of the roof (2) is held by the printed walls, thanks to a network of cavities in which the profiles could be inserted when the earth reaches a dry enough state. The working methodology for the design of the structural

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solution and corresponding deformation of the curve pattern was defined as a series of inputs from our collaborating structural engineers (SOCOTEC), and by conducting digital structural simulations.

The printed wall also provides for embedded custom-made timber furniture (3), which is inserted within the deformation of the wall. The working process focused on using the human body as an input, feeding real-time data through virtual reality, and generating digitally modelled furniture solutions.

Several carpentry details (4) were designed in order to create connections between timber elements, such as doors and windows, and the earth walls. In all cases, the strategy remains the deformation of the curve to create a local condition that facilitates the connection to timber profiles and to ensure avoiding a loss in thermal performance. These details were designed as a collaboration with a local carpenter (Lucas Fertig), and then physically constructed and tested both structurally and thermally. Additionally, digital thermal simulations were conducted in order to back up the digital tests.

Three deformations occur for the following climatic purposes: ventilation, light, and thermal transmittance. Natural ventilation (5) is achieved by designing a printing curve that provides not only a cavity in the wall, but also the space for the insertion of a wooden case that can both open and close (to cater for the different climatic needs of the Mediterranean summer and winter). The working methodology focused on developing fluid dynamic tests both physically and digitally (CFD analysis) and

4. Photograph showing the building process of the 3D-printed house project, TOVA. © IAAC + WASP.

5. Drone top view from the construction site of TOVA. © IAAC + WASP.

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recording the effect on printed geometry on the intensity of the flows. The conclusions served to select and further model the wall geometry that most efficiently permits the flow of air from the outside to the inside of the wall.

Thermal transmittance (6) is achieved by varying the thickness of the wall and the sizes of its cavities. This results in lengthening the printing curve, achieving wall sections with higher or lower mass and therefore affecting the time needed for heat to travel across the wall section. In order to understand the effect of geometrical changes on the curve, thermal simulation software was used to quantify, in minutes, heat transfer on a series of iterations of wall sections and printing paths. In order to verify the conclusions, the results of the digital tests were then compared with physical data extracted from a physical testing setup.

Light (7) porosity is achieved by creating discontinuity in the curve, which enables the creation of a network of small openings (10cm wide by 40cm high). The geometry of the curve is derived from sun path analysis to control afternoon light radiation, which is no longer harmful in terms of solar heat gain. These strategies were methodologically verified by digital simulations and physical models. The design approach is based on the creation of various iterations of wall geometry and their testing in order to evaluate and rank their performance in terms of light porosity.

A special focus of TOVA was given to the water resistance (8) of the façade. Raw earth façades are not waterproof unless non-natural products are used, either directly in the mix or as a coating, which leads to contamination of the earth. The walls of TOVA were printed with a mixture of entirely natural materials and aggregates. Therefore, the façades are vulnerable to water erosion if exposed directly to rain. In order to improve resistance, a common vernacular strategy from the Arabian Peninsula was used, which consists of inserting stones on the façade that interrupt the flow of water.

In TOVA, this approach is translated to an integrated manufacturing scenario by offsetting the façade curve by 2cm and at intervals of 15cm in the verticality on the layer-by-layer printing. The superior edge of the material offset is finished by a material plaster. In order to demonstrate the viability of this strategy, laboratory experiments were carried out by dropping water droplets at regular intervals onto different wall solutions.

The final design including all these intricacies and details results in a continuous printed path curve of 11.9km in length. The importance of this continuity relies on the

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reduction in air travel motion, also known as stop-start procedures in AM, which could otherwise cause poor surface finish and path breakage. The continuous particularity also reduces the total amount of print time required, as well as limiting the possibility of clogging in the system.

Results

Construction

This design has driven the 3D-printing process of TOVA over a period of seven weeks. The construction solutions developed for TOVA enable 98% of the materials to be locally sourced, either from natural or recycled sources. The foundation is made of recycled demolition materials encased in a metal grid cage or gabion. The base of the wall is cast from a mix of earth and geopolymer (recycled from the metal industry), shaped by an earth 3D printed formwork that is then recycled at a later stage. The walls are 3D printed from the same soil excavated for the foundation, sifted, and mixed with natural fibres (sisal), bio-additives (enzymes from sugar cane), and water. The roof, windows, and furniture are made of wood that could be sourced from the forest nearby. Only the glass and the metal connectors are not made from recycled or natural materials (Fig. 3).

The details integrated into the design have allowed the earth to be 3D printed without serious complications, while allowing easy and fast assembly of the components that are not 3D printed (Figs. 4, 5, 6). During the drying process, the curved surface and details deformed and settled, with small cracks appearing, mostly in predictable areas. After six months on the construction end, control measurements were executed on the prototype and the materiality; the latter seems to be fully dried and has not moved much from its initial position (as of the time of writing, 18 months later).

Resulting building

The result is a house demonstrator of 9m^2 that can be easily 3D printed from earth, and integrates structural, climatic, ergonomic, and architectural performance in all its detail (Figs. 1, 7). The combination of the design process and the fabrication method could reduce the embodied energy by more than 90% compared with a conventional building of a comparable size. The resulting dwelling aspires to be comfortable with minimal energy requirements: no need for air conditioning in summer (-8ºC temperature differences between inside and outside have been observed on the hottest day of the summer), and good thermal insulation for winter.

Conclusion

TOVA demonstrates the potential of a design methodology aiming to integrate all the complexities of 3D printing with earth with the challenges of architecture into the construction of small houses. The design methodology has been tested on digital design at a larger scale. Further developments are required to scale up this methodology on larger construction sites. Moreover, the digital workflow needs further simplification and validation to be accessible to less computationally fluent architects.

6. Assembly process of the roof. © 3DPA 2021-2022, Institute for Advanced Architecture of Catalonia, WASP.

7. Detailed view of TOVA façade pattern, IAAC + WASP. © Gregori Civera.

In conclusion, this case study showcases a new set of tools and methods that combine performative optimisation with flexibility and creativity in design, setting the base for further explorations on adaptive constructions, guided by context-specific material, climate, and culture, towards a sustainable and inclusive architecture.

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IMPACT PRINTED STRUCTURES
DESIGN SYSTEMS AND CONSTRUCTION STRATEGIES

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Introduction

The construction industry contributes significantly to environmental degradation through pollution, waste generation, and climbing greenhouse gas emissions, prompting the exploration of alternative materials with lighter environmental impact. The use of earth as a building material has been common in construction for centuries, offering advantages like high thermal inertia, moisture regulation, fire resistance, and acoustic insulation, which are ideally suited for construction. However, most traditional earth-building methods are formwork-dependent and labour-intensive, resulting in slow build rates and high costs. These shortcomings present a significant opportunity to leverage novel digital construction techniques for non-standard but sustainable materials such as raw earth.

To address these challenges, this research presents the design and construction potentials of a novel robotic earth-building technique called 'impact printing' (IP). The robotic building process resembles a 'shooting' process from a close range, where discrete malleable parts of the material are deposited at controlled high velocities and frequencies by a custom mechanism, resulting in monolithic material structures. Like traditional adobe or cob construction, the IP process utilises a custom material mix in a plastic state that gradually gains mechanical strength as it dries. A custom low-carbon earth-based material is developed for the IP process using minimal hydraulic binders. This development aims to enhance and control the curing rate and boost the compressive strength of the structure. The high-payload IP mechanism is mounted on a bridge-like superstructure controlled by a 3-axis gantry. This configuration facilitates a free unrestricted movement of the mechanism in Cartesian space, achieved through the synchronous control of two external axes within a multi-axis robotic gantry system.

The paper outlines a set of computational tools and construction strategies necessary to effectively use the IP process. The use of these methods is demonstrated through the design and fabrication of customised building components, such as columns and walls featuring architectural elements like doors and windows. In summary, the research presents the IP process as a viable solution for sustainable digital construction, facilitating the industrialisation of earth-based construction and fostering innovative design opportunities.

1

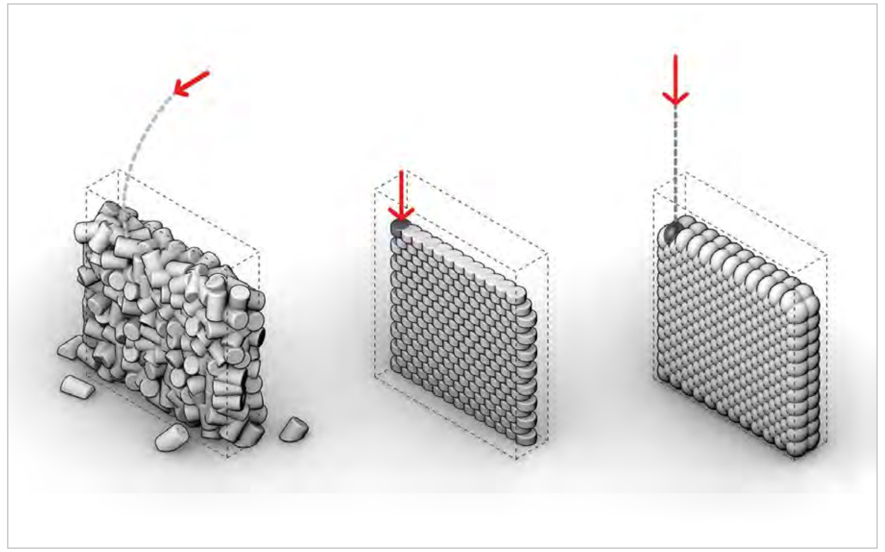
Impact printed structures

The construction sector holds a global reputation for its negative environmental impact and wasteful practices, primarily from the extraction and processing of building materials (Çetin *et al.*, 2021). The construction sector faces further criticism for its consistently low annual productivity, largely attributed to the conservative nature of the sector and the slow adoption of digital technologies (McKinsey, 2017).

Adopting additive manufacturing (AM) techniques in the construction industry is geared towards digitising construction sites and enhancing material and production efficiency, with concrete being the most commonly used material. However, the material mixes used for 3D concrete printing (3DCP) leave a higher carbon footprint and have reduced durability compared with standard reinforced concrete construction (Flatt and Wangler, 2022). In parallel with 3DCP developments, the past decade has seen a growing interest in processing sustainable materials with digital manufacturing techniques, including raw earth. Raw earth has been used as a building material for centuries because of its abundant availability and, thus, is cheaper at cost. In addition, earth has been used for construction with local knowledge and requires minimal manufacturing energy. But the reliance on manual labour and the necessity of formwork in most earth-building methods contribute to a slow and costly construction process. Even traditional earth buildings tend to be slow and over-priced.

Contemporary research has concentrated on modernising traditional building techniques to improve efficiency and economic feasibility. Notable examples include Gramazio Kohler Research's digitisation of cob construction in the Clay Rotunda (Gramazio Kohler Research, 2021), Technical University of Braunschweig's implementation of the robotic rammed earth process (TU Braunschweig, 2022), the endeavours of organisations like World's Advanced Saving Project (WASP), the Institute for Advanced Architecture of Catalonia (IAAC), and Emerging Object in integrating extruded earth methods (WASP, 2021; Dubor *et al.*, 2019; San Fratello *et al.*, 2020), and Mudd Architects' adaptation of the wattle and daub technique in the Mud Shell project (Mudd Architects, 2019).

When adapting extrusion 3D printing for earth-based materials, the process tends to be slower and necessitates a high percentage of mineral-based stabilisers such as lime or cement, which offsets some of the environmental advantages. As a result, there exists a trade-off between construction efficiency and environmental impact. Hence,



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there is a need to explore alternative digital techniques and AM methods, specifically for dense earth materials, that offer improved efficiency, reduced reliance on additives, and cost-effectiveness.

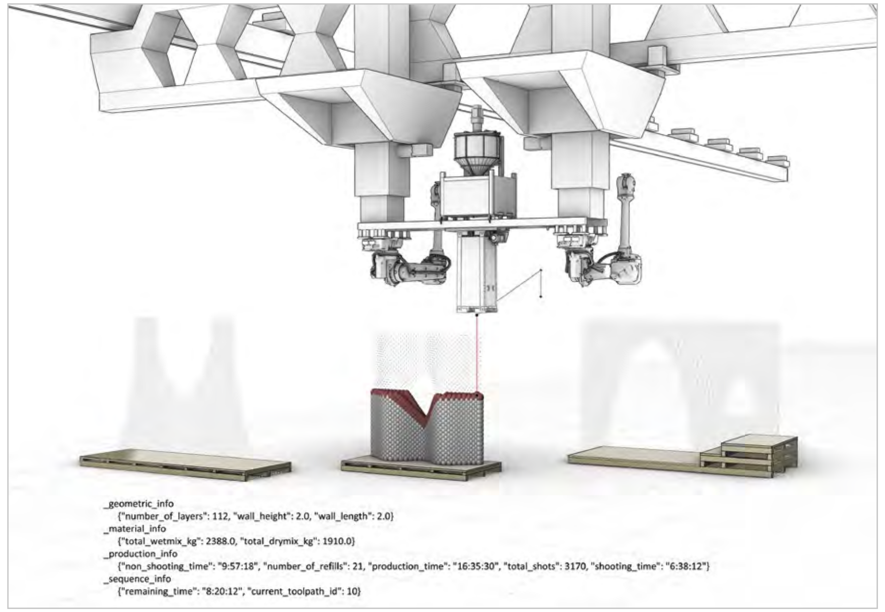
A novel robotic earth-building method

IP is a novel AM process that deposits discrete portions of malleable material at high velocities to improve interlayer bonding and compaction without formwork. This paper presents the progression and upscaling of IP for one-storey volumetric structures (Ming *et al.*, 2022), building on the precedent research of Remote Material Deposition (RMD) (Dörfler *et al.*, 2014) and the Clay Rotunda project. RMD introduced a 'throwing' method with extended reachability but limited control and longer cycle times. In contrast, Clay Rotunda employed a 'pressing' technique for precise deposition control but limited by operational constraints and slowness, mainly caused by the time taken by the robot to move between the prefabricated earthen parts and their intended positions. Additionally, both methods involved using cylindrical earthen parts for deposition, which had to be prefabricated off site, thus adding transportation costs to the production process. These constraints pose challenges for scaling up these processes for commercial applications.

Synthesising the two previously mentioned technologies, IP uses a short-range remote deposition process of 'shooting' at high velocities and frequencies. The process holds the potential for efficient volumetric build-up due to the compaction achieved on impact. While the approach has successfully produced continuous construction of

1. Full-scale prototypes of *Impact Printed Structures*, fabricated at the Robotic Fabrication Lab at ETH Zürich, using a custom end-effector mounted on two gantries programmed for synchronous operation. © Michael Lyrenmann, ETH Zürich.

2. Illustration showing high-level concepts of precedent and current techniques at Gramazio Kohler Research used to fabricate with discrete malleable earth parts: (a) 'throwing' technique used during Remote Material Deposition in 2014, (b) 'pressing' technique used during Clay Rotunda in 2021, and (c) 'shooting' technique currently investigated during *Impact Printed Structures*. © Kunaljit Chadha, ETH Zürich.



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3. Screen capture of the design and planning environment displaying the construction date in the bottom left corner and highlighting the construction sequence presently followed in the fabrication setup. © Kunaljit Chadha, ETH Zürich.

vertical structures up to 1.5m high, further testing is required to fully validate the potential of the IP process for volumetric and customisable construction.

IP was developed as an AM method that can be adapted for off-site pre-fabrication, on-site pre-fabrication, and in-situ monolithic construction. The presented work is an outcome of ongoing research on the design and construction potentials of the IP process in a pre-fabrication context. The subsequent phase will involve transitioning to on-site testing in a less structured environment, utilising the autonomous excavator created by the Robotic Systems Lab at ETH Zürich (Jud *et al.*, 2021). Thus, the custom IP mechanism was developed and integrated to be compatible with high-payload gantry systems and autonomous construction machines.

In the presented work, the IP mechanism consisting of extrusion, portioning, and shooting sub-systems arranged in a vertical stack is mounted on a bridge-like structure to distribute the payload between two external axes. The IP mechanism can be manoeuvred freely in Cartesian space with a fixed orientation by synchronous control of two external axes of a multi-axis robotic gantry system in the Robotic Fabrication Lab (RFL) at ETH Zürich. Currently, the tool can extrude parts weighing between 0.75kg and 0.8kg at an average cycle time of 7.5 seconds.

The software architecture consists of four communicating modules: a CAD design and planning environment, a tool-controller PLC, a robot controller, and a high-level controller with a Linux PC to synchronise all processes. To design and visualise architectural structures, a custom design library is developed using the RhinoCommon library, with Rhino serving as the CAD planning environment. Individual toolpaths containing building sequences are sent directly to the high-level controller using COMPAS FAB (Casas *et al.*, 2023) with necessary position and timing information. The high-level controller then communicates at high frequencies with both the robot controller and the tool-controller PLC to synchronise the dispatching of the parts at planned target positions.

The IP method uses a batch-mixing process for material processing, where premixed material is manually fed to a screw-based extrusion system. In this context, the critical factor regarding the material state is the yield stress, representing a material's ability to endure stress before permanent deformation (Coussot, 2014). In contrast to extrusion-based methods, IP allows for plastic deformation upon impact, meaning that the material, in its malleable state, must endure both forces due to impact and cumulative weight. Hence, through empirical testing, the initial yield stress of the material for the IP process is calibrated between 26 and 28kPa. In traditional methods, like cob construction, the material contains fine particles (<63µm) with clay at 15 to 20% of the total mix. To adapt a comparable mix for the IP process, adjustments are made to increase the content of fine particles, enhancing the internal cohesion of the material. This modified material mix was developed in collaboration with the Chair of Sustainable Construction at ETH, utilising locally sourced materials rich in fine particles such as clay and silt. By employing a material mix with reduced water content and incorporating as little as 2.5wt% of commercial hydraulic lime, the objective is to expedite early strength development for the IP process.

Design challenges of building with earth

Earth construction inherently presents many design and construction challenges due to the malleable and variable nature of the material. Earth structures typically take a long time to dry, and there is a tendency for uneven shrinkage, leading to issues like building tolerances, cracking, and structural failures under varying environmental conditions. This unpredictability hinders the design process and limits the range of design possibilities in both traditional and automated methods. Additional challenges involve maintaining structural stability during construction and preventing cold joints. Structural failures such as plastic deformation, layer delamination, and global buckling must be considered and mitigated during construction. Beyond the construction phase, regular repairs and maintenance are key topics in constructing durable structures out of earth. These challenges present an excellent opportunity to address the issues by re-evaluating the materials used and exploring new and inventive construction methods.

The unique IP process poses additional distinct challenges as compared to other AM techniques. For extrusion-based 3D printing, plastic failures due to self-weight are mitigated by modifying and increasing the early strength development of the material. In contrast, with IP, the load cases experienced during construction include both self-weight and impact forces. Consequently, IP necessitates suitable computational design methods and construction strategies that align with the production method and the unique load cases during construction. Preliminary tests have suggested that the combination of the higher yield stress at which parts are deposited, and the high-velocity deposition of the IP process enables higher stable volumetric build-up compared with other AM methods, particularly conventional extrusion-based printing. The printing efficiency in terms of volume per time has to be further investigated and optimised.

To demonstrate the potential of IP as a building method, a series of prototypes are built that focus on designing and fabricating customised load-bearing building components, such as columns and walls featuring architectural features like doors and windows. The design and fabrication processes were implemented and evaluated within the context of a semester-long course offered in the Master of Advanced Studies in Digital Fabrication (MAS DFAB) programme at ETH Zürich.

Computational design system

When designing with the IP process, a primary challenge lies in breaking down the intended volumetric construction into discrete components that must be deposited in specific sequences. Unlike traditional brick stacking, these discrete parts are malleable in state and take on an elliptical shape due to the compaction process before deposition. Their deformation is additionally influenced by factors like the material's yield stress, deposition velocity, and the positioning of neighbouring parts; thus, the spacing between the parts must be precisely planned to avoid undesirable and uncontrolled vertical build-up. It is also crucial to computationally handle the spacing of the parts in subsequent layers to prevent them from dislodging or bouncing off previous layers as a consequence of the impact of the deposition process.

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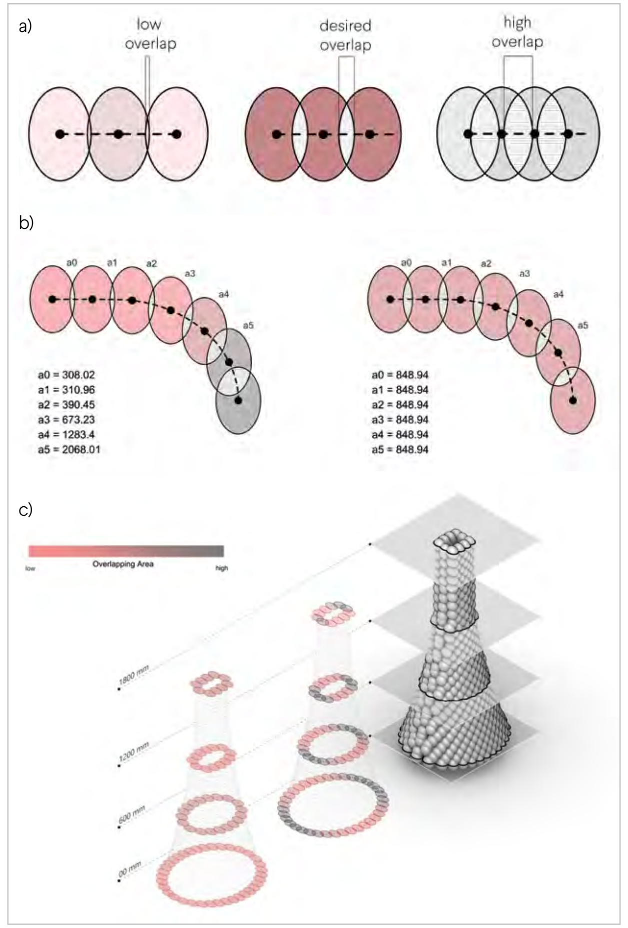

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4. Results of successful design and fabrication of novel wall and tapered column structure combinations incorporating timber elements. The earth and timber combination achieves a levelled surface suitable for potential use in flooring or roofing applications. © Michael Lyrenmann, ETH Zürich.

5. (a) Spacing logic to visualise overlapping areas between successive parts, (b) a comparison of part distribution along a curved toolpath between spacing by distance and iterative spacing, and (c) planar sections demonstrating the effective application of iterative spacing for a tapered column with varying toolpath lengths across different layers. © Kunaljit Chadha, ETH Zürich.

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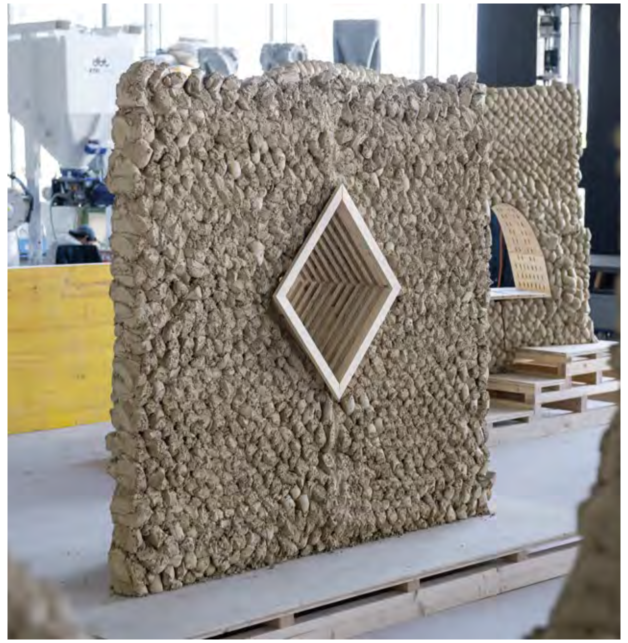
6. Image of a three-layered structure with an integrated arch opening during construction, illustrating even distribution of parts along a curved toolpath. © Nijat Mahamaliyev, ETH Zürich.

An object-oriented library and a set of computational tools are developed to generate valid impact printed designs. These tools consider the constraints from the fabrication setup, specifically collision, and manage the generation of discrete parts and building sequences. The developed computational tools also allow the previewing of construction sequences and outputs of construction data for planning production logistics.

To deal with the complexities of the IP process, computational methods are devised to achieve uniform part distribution along the deposition toolpath for diverse geometric conditions, including variable curvature and thickness. An algorithm initially distributes parts equidistantly along the toolpath, then iteratively refines the spacing until a consistent overlap area is achieved. This method enables the design of IP structures featuring higher degrees of curvature and variable toolpath lengths to enable formal variants like tapered columns. Addressing the spacing of parts in subsequent layers, a diagrid sequencing strategy is developed to ensure an alternating deposition pattern in these layers. This strategy ensures the consistent deposition of each part within the voids between parts on previous layers, thereby preventing any dislodging.

The fabrication of impact printed structures presents challenges due to the time-sensitive nature of material curing. This necessitates careful coordination between all fabrication process parameters, including material mixing, feeding timing, and machine capacity. Hence, planning tools are needed to integrate these process constraints into design and production planning. To facilitate this, a computational planning tool generates building sequences and outputs construction data. At present, the fabrication setup uses an automated batch-mixing approach, which needs timely refilling. Therefore, the intended structure is divided into individual toolpaths, each containing 50 parts, aligning with the prevailing material capacity of the extruder. The construction data provides quantitative insights into production, including parameters such as the total number of parts, material quantities for mixing, and predicted deposition time for each sequence. This tool enables users to make informed decisions while planning material mixing schedules, allowing for the parallelisation of tasks to minimise machine downtime.

In contrast to layer-based 3D printing, where the extrusion nozzle is in contact with the printed structure, raising the possibility of collisions while embedding external elements, the non-contact process of IP allows for discrete and non-planar sequencing for construction. This approach allows for the integration of functional architectural elements into structures during the construction process. Successful tests have been conducted, depositing material from heights ranging between 0.2 and 2.0m above the intended parts. To explore this potential further, a series of prototypes feature geometrically non-standard architectural openings that effectively function as doors and windows. Embedded timber frames are placed and pushed into position during the IP sequences to achieve



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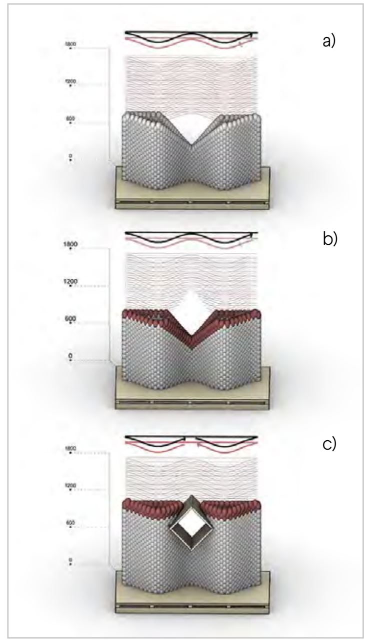

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integrated elements. The vertical tool offset distance is adjusted to prevent the tool from colliding with the frame. With the possibility of building with a non-planar sequence, strategies are developed to selectively deposit a fresh layer of material underneath the embedded frame, preventing the occurrence of dry joints in the structure.

Additionally, within the computational framework, each part is assigned a unique identifying number (UID) and stored to log the success of deposition. Together with the online communication with the fabrication setup, the UIDs allow for dynamic regeneration of the construction sequencing at the last successful shot location in cases of fabrication error.

Construction strategies

Overall stability is an important consideration in the IP process, during both the building and curing phases. With deposition velocities as high as 9.5-10.0m/s, the resulting impact force can be estimated to be more than a hundred times the self-weight of a single part. Therefore, it becomes imperative to implement temporary stabilisation measures to withstand live loads during construction, preventing potential snags like global buckling and overturning failures. Furthermore, building components, such as timber frames, integrated into the construction process must be temporarily stabilised and kept steady until the material has cured to avoid uncontrolled displacement.

To address these concerns, three distinct strategies, to ensure the stability of the structure and prevent deformation and structural failures during construction due to the impact force of material deposition and the weight of the material, are developed and tested. These strategies comprise: a) edge constraints, where supports constrain the edges of the structure to ensure consistent build-up, b) removable infills using loose aggregates as temporary internal supports for creating overhanging sections, and c) adjustable props to provide temporary stabilisation for embedded elements forming openings, which are removed once the construction material has sufficiently cured.

Shrinkage is a long-drawn-out issue with earthen construction, as it involves using a material mix that requires adding water to form a workable compound for construction. This leads to uneven deformations in the structure and cracking during curing, arising from ambient conditions and local stress concentrations. Two distinct construction strategies are developed to address the challenge of shrinkage within the IP process. The first approach focuses on controlling cracking and involves deliberately designing gaps or high-stress concentrations in strategic locations of the structure to induce the formation of cracks that can be manually repaired. This approach minimises the probability of unexpected cracks and enhances the overall reliability of the construction process. The second approach is native to the IP process, and tackles the cracking caused by the impact forces upon externally embedded building components. The approach focuses on mitigating the cracks by embedding rigid timber elements within the structure during construction. These elements are strategically placed along the length of the toolpath to ensure an even distribution of impact forces, thereby addressing the problem of cracking induced by the impact force of the parts.

7. Results from the successful prototyping of a double-layered wall with a diamond-shaped opening displaying the use of non-planar sequencing. © Michael Lyrenmann, ETH Zürich.

8. This involves (a) non-planar sequencing to direct the placement of the frame, (b) adding an extra layer to ensure a fresh material is deposited beneath the embedded timber frame for the opening, and (c) a customised order of deposition, starting from the outside and moving inwards to stabilise the frame. © Kunaljit Chadha, ETH Zürich.

9. Temporary props stabilising the frame during the IP process. Right: Employing a formative process to ensure the evenness of the upper surface of the columns prior to the installation of the roofing element. © Kunaljit Chadha, ETH Zürich.

Conclusion and outlook

In sum, the IP process adds to the enduring tradition of building with earthen materials. It presents a low-cost, waste-free building method that incorporates high levels of design control while using local materials with low environmental impact. The presented work underscores the pivotal role of computational design and building strategies in employing IP to create new architectural forms characterised by compacted, free-form volumes. Moreover, the successful demonstration of integrating other building components within the IP process not only expands the range of potential applications in the field of architecture but could facilitate the industrialisation of hybrid earthen construction systems for commercial purposes.

The rough surface of structures built through IP, characterised by its high-speed but low-resolution building process, suggests an interesting prospect for secondary surface finishing strategies. Furthermore, the material employed in IP stays workable for an extended duration and can enable secondary refinement and detailing and integration with other systems. The future implementation of the IP tool on the HEAP excavator will provide an opportunity to evaluate the reliability of the computational methods and construction strategies on site in an unstructured environment. The possibility of orienting the tool and shooting from different angles because of the multiple degrees of freedom of the excavator can further help to explore designing and fabricating structures in uneven terrain.

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BREUER X AM
FUNCTIONAL HYBRIDISATION IN CONCRETE BUILDING ENVELOPE ELEMENTS THROUGH ADDITIVE MANUFACTURING

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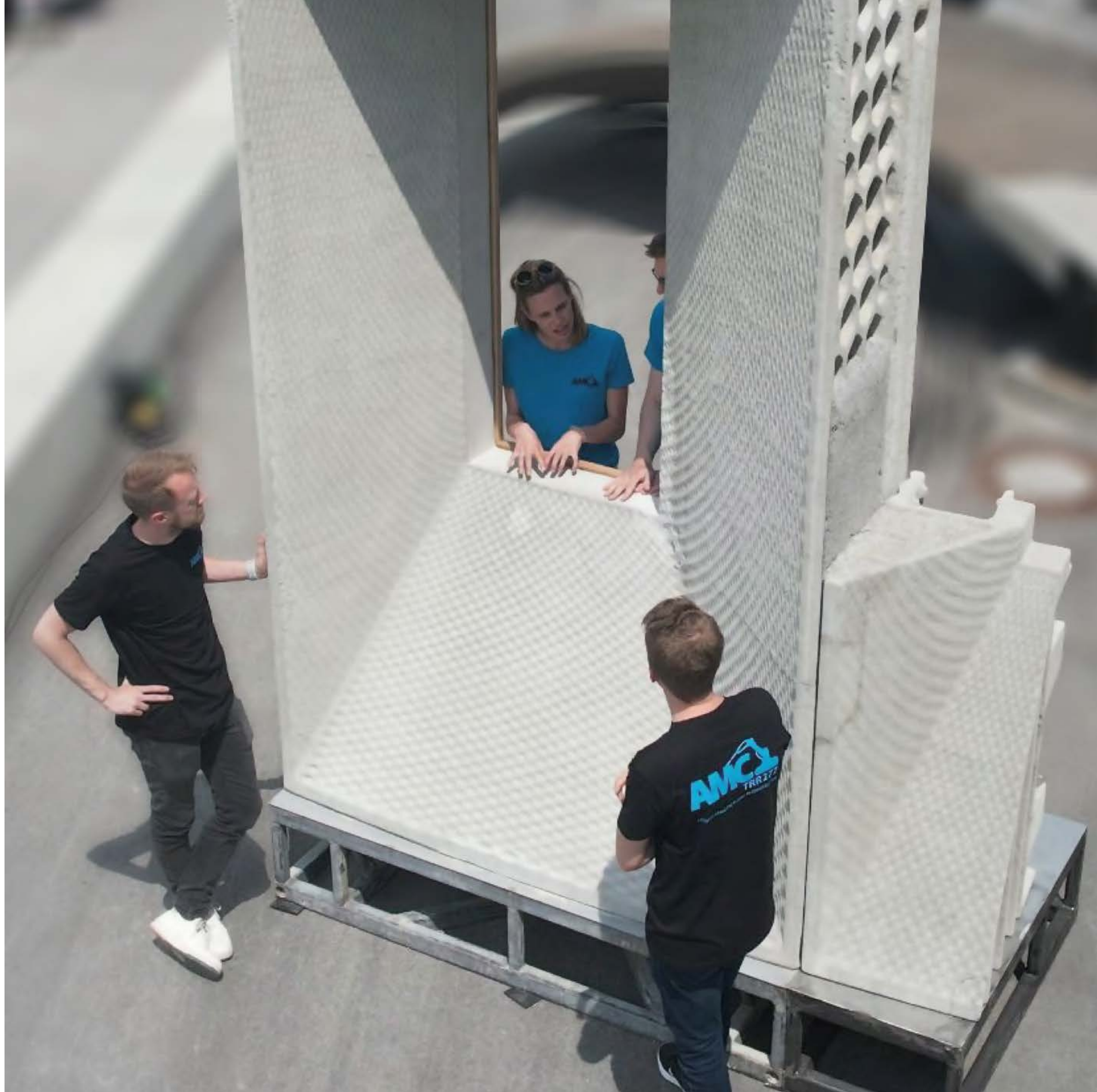
Introduction

Additive Manufacturing in Construction (AMC) provides a high degree of design freedom, capable of integrating complex functional requirements with streamlined manufacturing processes. In traditional industrial construction, adherence to standardised practices often necessitates the division of building functions across multiple layers and materials. This is done to comply with structural and functional guidelines outlined in building codes, as well as to incorporate active and passive heating and cooling systems in building envelopes.

In the 1960s, architect Marcel Breuer introduced pioneering methods to address the complexities of multi-layered building systems. His visionary approach, exemplified in projects like the IBM Research Center in La Gaude, France, sought to synthesise building services, installations, and passive solar protection measures into a single modular precast façade panel. His design approach involved the manual calculations of solar angles and graphical methods to obtain desirable shading properties for the building envelope elements. However, the manufacturing constraints imposed by concrete casting techniques posed limitations on the ability to create bespoke variations, necessitating an excessive reliance on standardised production of identical elements (Fig. 2).

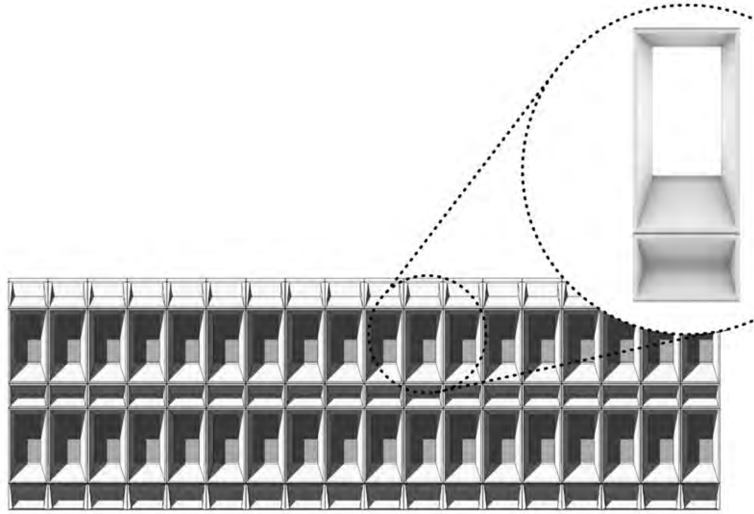
AMC technologies offer unique design flexibility to address both the need for functional integration and adherence to building codes and non-standard and bespoke production possibilities by leveraging geometric differentiation. Going beyond multi-layered and multi-material building systems, functional integration and hybridisation in mono-material building systems further enable the attainment of sufficient dismantlability and circular material utilisation at the end-of-life stage of building envelope elements. Within this context, this research explores how AMC technology can be utilised to expand the concept of prefabrication of concrete elements towards functionally integrated and hybridised building envelope elements while reducing the materials used. As such, this research comprises: a) a bespoke volume and surface design of individual building envelope elements in an overall building envelope, b) the structural zone design, and c) the thermal zone design of the internal structure of these bespoke elements (Fig. 3). The proposed methods were experimentally tested and validated by producing a 1:1-scale demonstrator using the AMC technology of Selective Cement Activation (SCA).



1. Drone image of the 1:1-scale demonstrator, oriented in south-southeast direction, set up on 5 June, 2023 at 13:30 at the Galileo in Garching bei München, Germany. © Janna Vollrath / TUBS.

Novel AMC technologies such as particle-bed 3D Printing (PB3DP) have transitioned from experimental setups in academia towards large-scale applications in the construction industry (Asprone *et al.*, 2018). SCA, a distinct PB3DP process, involves applying a liquid activator to compressed layers of a mix of dry aggregate and mineral binder, such as dry cement, typically comprising fine grains <1mm, with a layer height of approximately 1.5mm. This technology, with high-resolution capabilities ranging from 1 to 3mm, allows for precise material deposition tailored to local structural and functional needs. It offers a durable, low-waste prefabrication method with expansive design freedom and without the need for formwork (Meibodi *et al.*, 2018; Herding *et al.*, 2022). This innovation not only serves the purpose of automation, industrialisation, and increasing resource efficiency, but also enables innovative approaches such as the integration of functions and their hybridisation through high-resolution geometric detailing (Agustí-Juan *et al.*, 2019).

In a broader context, large-scale SCA is well suited for prefabricating concrete elements. However, the production of large-scale SCA building elements also presents considerable challenges, primarily due to material shrinkage and the potential for cracking, as well as the mechanical properties inherent to the material system. These complications are coupled with the intricacies of part handling throughout the process, including the extraction and transportation of printed elements from the powder bed. At present, SCA exhibits a lower mechanical strength, featuring a flexural strength of 2.5MPa, compressive strength of 12.0MPa, and a density of 900kg/m^3 (Richter and Jungwirth, 2023) compared with cast concrete elements with a similar density, such as infra-lightweight concrete, which boast a flexural strength of 3.0MPa, compressive strength of 13.0MPa, and a density of 780kg/m^3 (Schlaich and Hückler, 2012). This discrepancy in strength contributes to the occurrence of early-stage cracking. Given the necessity for prefabricated load-bearing building elements to withstand high stresses during transport and structural application, one potential solution is the combination of lightweight SCA, applied locally as a stay-in-place formwork for cast reinforced concrete, to enable robust structural implementations. However, it is worth noting that the density and mechanical strength of lightweight SCA material systems closely approach the upper limit for state-of-the-art infra-light concrete defined in the German Building Standard DIN EN 206-1.



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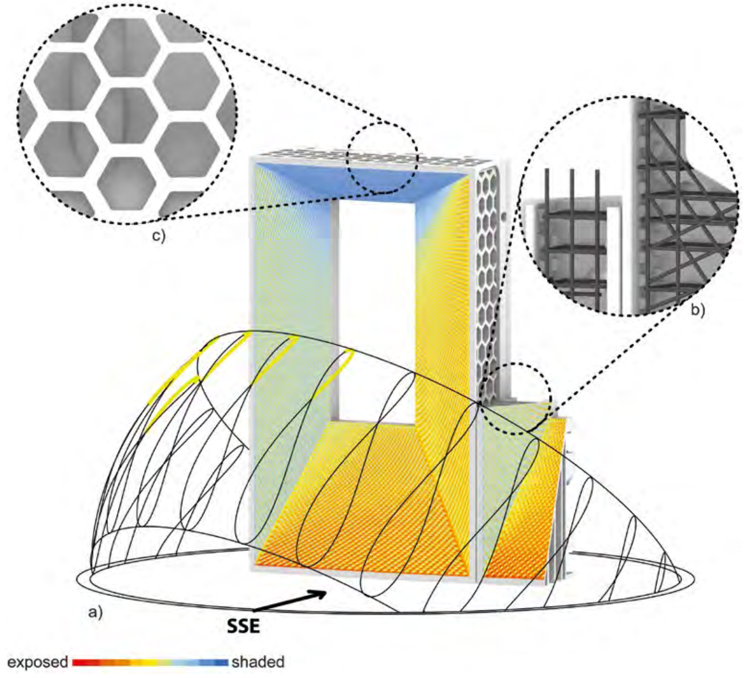

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2. Elevation of architect Marcel Breuer's precast solar-controlled standardised building façade panels.
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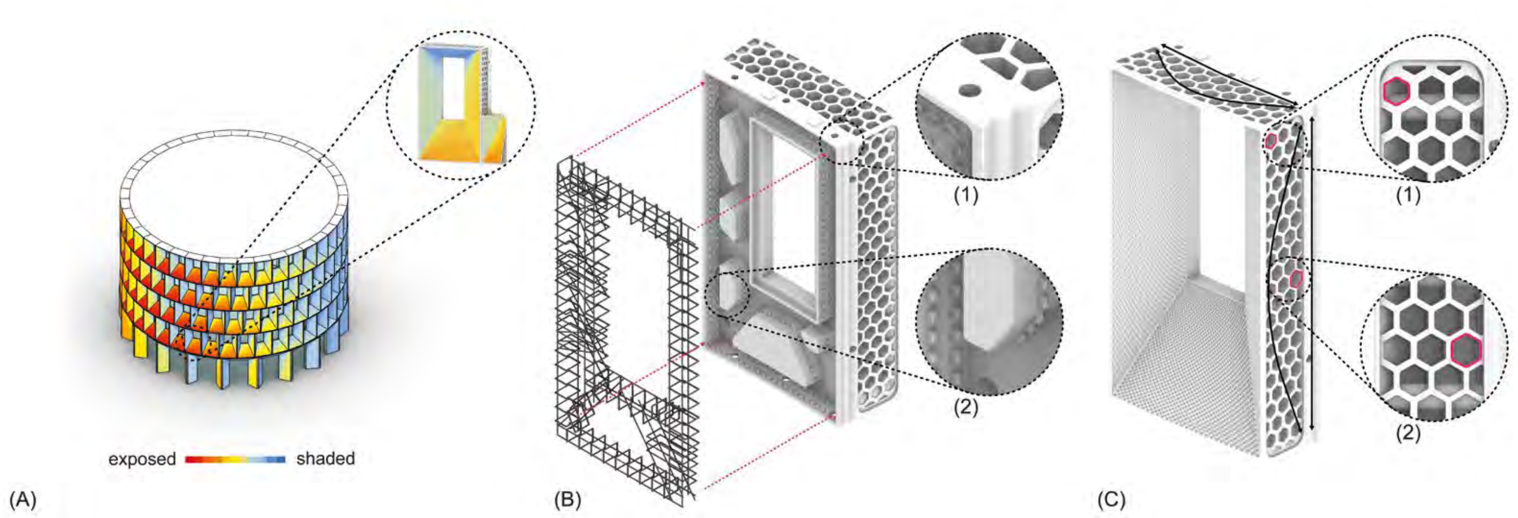
3. Functionally hybridised building envelope element of the 1:1-scale demonstrator: (a) Solar-controlled volume and surface design, (b) Structural zone design as a stay-in-place formwork for casting reinforcement (~20cm width), (c) Thermal zone design as a graded cellular structure (~50cm width).
© Julia Fleckenstein / TUM.



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4. The geometric design of the individual building envelope elements, based on a circular building layout (A) serves as framework for the functional hybridisation of both structural (B) and building physical (C) requirements. In the structural zone (B), dry joints (1) on the outer sides are positioned to support the assembly of adjacent elements onsite. Simultaneously, the zone functions as notched and customised lost formwork (2) for casting a rebar cage and loadbearing anchors. The thermal zone (C) is open to all four sides, featuring cells that vary in both horizontal and vertical directions, providing ample rigidity for the front edges. Here, (1) indicates the smallest cell, while (2) represents the largest cell.
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Further crucial considerations for the functional integration into SCA building elements involve the removing of inactivated powder from the printed component and the necessity of open-cell structures to prevent cement powder entrapment in closed geometries. It is thus essential to consider only open-cell structures that are easily accessible from the exterior and sufficiently spacious to accommodate the insertion of a suction hose for excavation (Lowke *et al.*, 2022). Achieving proper material adhesion at the interface between activated and deactivated powder also presents a challenge.

While research on AMC processes with SCA has been ongoing, the large-scale integration of SCA into architectural applications and the development of multi-functional design approaches remain significantly unexplored. Consequently, this research aims to investigate the potentials and constraints of utilising SCA for the proposed hybridised design objectives at a 1:1 scale, presenting an expansion of traditional concrete-element prefabrication methods.

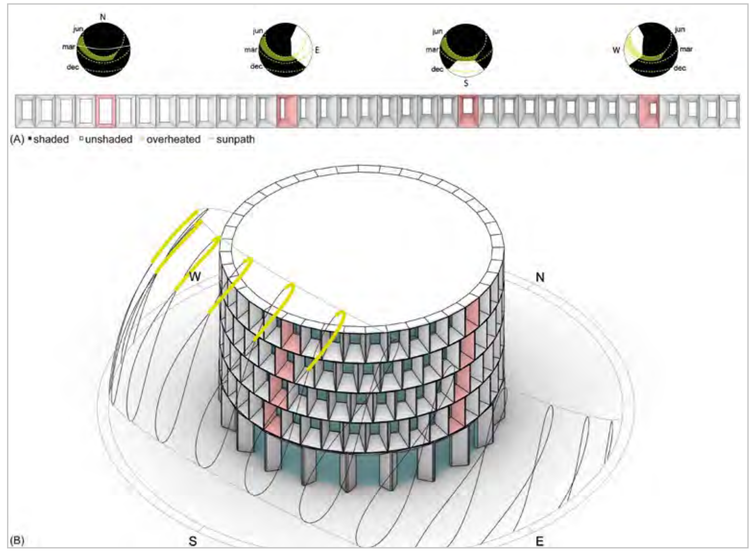
Method

Drawing inspiration from the architectural reference of Marcel Breuer's prefabricated façade system, a method for the design and prefabrication of AMC building envelope components has been developed in this research. This method harnesses SCA technology to overcome present industrial manufacturing constraints and unlock opportunities for localised variations and customisation. This method encompasses the following steps: a) Tailoring the volume and surface design of individual building envelope elements within the overarching building envelope by using graphical methods to respond to specific local solar exposure conditions (Fig. 4A), and, concurrently, designing the internal structure of these elements, which includes integrating the design of b) the structural zone (Fig. 4B), and c) the thermal zone (Fig. 4C).

The development, testing, and assessment of this design-to-fabrication method were undertaken within the context of a case study involving the design of a multi-storey building. Ultimately, a full-scale demonstrator of two building envelope elements from the building design was fabricated using SCA technology. This demonstrator was designed and planned as a functional hybrid to validate the general applicability of the computational design approach of functionally integrating both thermal and load-bearing requirements, as well as the fabricability with SCA technology of such a large-scale building envelope element.

SCA material system

In this research, the AMC technology of SCA was chosen and customised to fit defined requirements, and its boundary conditions were used as key design drivers. First, the layer height of the PB3DP method was set to 1.5mm requiring the use of sub-millimetre aggregates to achieve such a high resolution. The material system was tailored to use locally available ingredients and standardised building products. Therefore, ordinary Portland Cement and unpurified soft water were selected as binding agents because of their wide availability and



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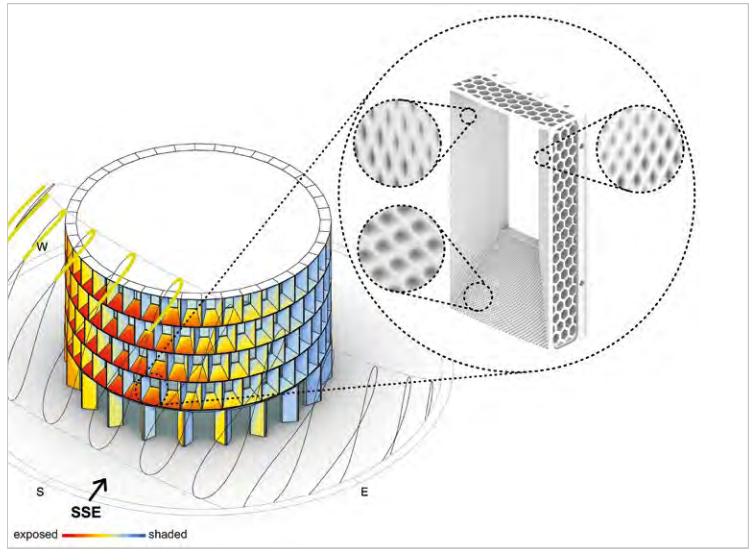

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cost-effectiveness in the construction sector. The chosen aggregates incorporated expanded glass particles (LEGA) derived from locally sourced glass bottles, thereby extending their life cycle. As ordinary Portland Cement was used as a binder, manufactured parts needed to be hydrated before being fully cured. The necessity of these additional steps demands part handling of the unreinforced green-state element and precise control of temperature and humidity. Additionally, the size of the print element is constrained by the size of the overall build space and varies according to the particle print setup between small and large print jobs, which are linked to different requirements as well.

Solar-control design strategies for the building envelope element's volume

Computational tools provide a precise means of simulating and implementing features that adapt to the varying levels of solar exposure on a building's envelope. In this research, we harnessed solar-control strategies to differentiate the design of the volumetric shapes of building envelope elements, building upon prior work by Bertagna *et al.* (2023). These solar-control strategies leverage graphical methods for shading building envelope elements, using a geometry-based model that relies on climate data as the only input parameter (e.g., Energy Plus Weather (EPW) file), along with the designer's intention for their overall shape. We developed an algorithmic design tool capable of translating design intentions into customisable parameters, granting the flexibility to modify depth, width, and length, as well as the vertical and horizontal positioning of the glazed area in each building envelope element. The objective of adjusting these parameters is to ensure ample daylight for the interior spaces throughout the year while effectively avoiding overheating, particularly during the cooling season. In the proposed case study, a circular building layout served for the exploration of the architectural variations across the overall building envelope design (Fig. 5). Employing the solar-control design method resulted in a building envelope composed of customised elements, featuring varying sizes for the glazed areas that ensure an adequate window-to-wall ratio, taking into consideration their unique orientations.

Solar-control design strategies concerning the element's surface

Additionally, we have adjusted the surface of the customised building envelope elements to incorporate self-shading properties using surface patterns, aiming to mitigate overheating on the surfaces adjacent to the glazed area resulting from the accumulation of solar energy, as discussed by Fleckenstein *et al.* (2022). These surface patterns were strategically designed to harness self-shading effects, effectively reducing solar heat gain and cooling loads based on locally varying requirements. The geometric patterns were carefully adjusted in terms of depth, size, and angle, to align with the prevailing radiation profile. Solar radiation simulations reveal that unmodified surfaces receive higher potentials of solar radiation than those with applied geometries. This implies that geometrically differentiated surfaces tend to have lower surface temperatures as a consequence of inter-reflections that reduce the direct solar exposure through their self-shading capabilities (Fleckenstein *et al.*, 2023) (Fig. 6).

5. (A) Solar-control aspects serve as input parameters for the algorithm-based design workflow tailoring the glazed area for the north, east, south, and west directions in width, height, and depth as well as in its vertical and horizontal translation to prevent the interior space from overheating. The solar masks above the elements indicate that the glazed area's adjacent surfaces cast enough shade (indicated in black) to prevent thermal overload during the cooling season (yellow), while still allowing sufficient daylight for the interior with the window-to-wall ratio varying for each element according to the sun's orientation. (B) Implemented in the design tool, each of these four elements is customisable to the local requirements, while the elements in between gradually self-align. The outcome of the solar-controlled design method is a building envelope composed of customised, solar-controlled building elements with varying sizes of the glazing area. © Julia Fleckenstein / TUM.

6. Elaboration of a building design section facing south-southeast for the AM of a demonstrator in real-building scale. A solar radiation simulation (red = exposed, blue = shaded) visualises the solar exposed surfaces of the building envelope elements tending to overheat during sunny summer days. A south-southeast-oriented building envelope element serves for the further elaboration of the demonstrator to validate the assumptions made from the simulations. Self-shading surface geometries are applied to gradually reduce exposed areas based on the colour codes of the solar radiation simulation. The more exposed the area, the stronger the depth of the pattern, and less exposed and more shaded surface areas feature a lower differentiation. © Julia Fleckenstein / TUM.

7. (left) The load-bearing zone is intended as a lost formwork for placing a prefabricated rebar cage and for casting grouted concrete. Evenly notched sides wedge the grouted concrete to the SCA material. Based on the idea of the force-flow, redundant material has been selectively extracted to only place the reinforcement and cast the grouted concrete where it is needed. (right) Triangulated connectors along the vertical length of the building envelope's side effectively secure the adjacent cut building envelope element in place. (left) © Gerrit Placzek / TUBS, (right) © Julia Bergmeister / TUM.

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Structural zone design

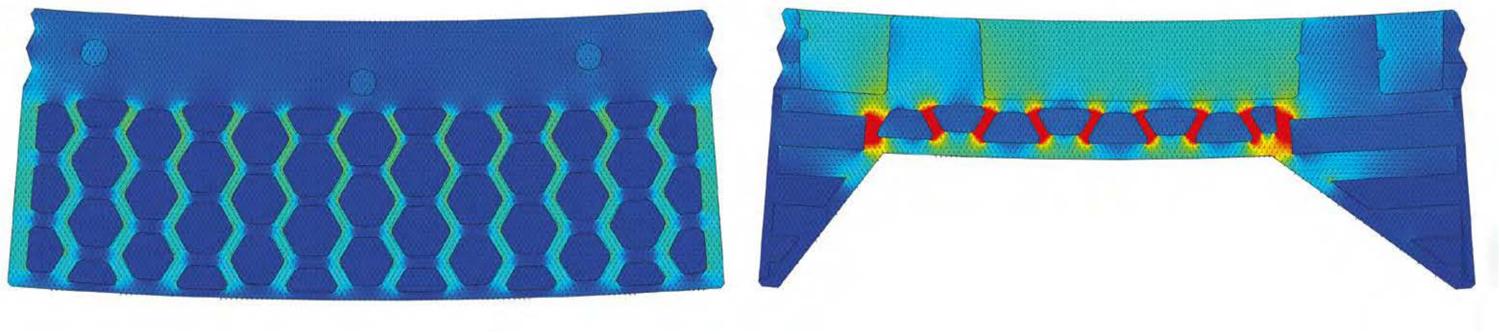
The load-bearing zone, with a width of ~20cm at its deepest, is designed as an additively manufactured stay-in-place formwork, offering the benefits of designing the optimal geometry for incorporating a prefabricated rebar cage as reinforcement and cast grouted concrete into the SCA element. This concept makes it possible to significantly increase the mechanical properties of the final building envelope element at specifically required locations. The stay-in-place formwork is customisable for varying thicknesses and non-prismatic shapes, facilitating the adaptation to non-standard geometries and enhancing versatility for construction projects with distinctive design elements and varying structural requirements. Preliminary tests assessed the general applicability and the bond between the grouting and the SCA concrete. As a result, the sides of the stay-in-place formwork were uniformly notched with the aim of enhancing the bond and facilitating a secure connection between the grouted concrete and the SCA material (Fig. 7).

For the structural zone design, the forces in the building envelope element have been analysed as part of the overall building design – that is, by considering gravity and lateral loads, resulting in a topology-optimised design based on the determined load combination. Subsequently, the applied forces were calculated for the building envelope element's rotation around its centre of gravity from the downward-facing front side to an upright position, and from there to the downward-facing back side. Based on this, the quantity and layout of the rebar were calculated as beam-column elements, resulting in a rebar cage with longitudinal rebar (ϕ0.12m, 1.30m) and stirrups (ϕ0.08m, 0.38m), along with additional necessary anchorages for transportation. To integrate the building envelope elements into the overall building system using a dry-joint assembly, two types of pretested, high-force-resistant geometries were employed: truncated pyramids on top and bottom and triangular connectors on the building envelope elements' sides. Given their simple geometry, they are expected to facilitate and accelerate the assembly process on site while transmitting the forces in the required degrees of freedom. In each area of the structural system, one side of the selected joint carries a specific force to the other side of the joint into the next joint of the adjacent building envelope element. This force transfer depends on the joint's rigidity, influenced by its shape, material, and position. Therefore, the joints were strategically placed within the structural, reinforced zone of the building envelope element and maintained during the topology optimisation (Lanwer *et al.*, 2022; Baghdadi *et al.*, 2023).

Thermal zone design

The insulation zone, extending to 50cm at its widest point, is designed to enhance the thermal performance of the overall building envelope element without the need for an additional layer of insulation. This zone features an open-cell structure, utilising a graded hexagonal cellular shape. The form-finding is supported by a simulation-based, parametric design approach based on two-dimensional heat flux simulations, and has been evaluated and compared in detail with other AMC processes and material compositions (Briels *et al.*, 2023c). To provide ample rigidity at the front edges and to meet the printing needs of the SCA process, the cell size varies between 80 and 100mm and the rib thickness between 20 to 40mm, allowing for the removal of unbound material. The cell structure is recessed by 2cm, creating a continuous cavity between the adjacent building envelope elements when assembled on site, connecting the individual cells. This allows for the injection of blow-in insulation material (e.g., perlite or cellulose) after assembly, significantly improving the overall insulation properties, compared with a solid element and air-filled cells (Briels *et al.*, 2023b). The final design's thermal performance was assessed using a heat transfer coefficient of 0.98W/m^{2}K, which was averaged across 20 layers (Briels *et al.*, 2023a).

The resulting heat flux density is visualised with a coloured mesh of two exemplary horizontal sections of the element in Fig. 7, illustrating the thermal throughput per area through the element ranging from blue (low thermal heat flux density) to red (high thermal heat flux density). The overall thermal performance is limited by the additional load-bearing zone, which has higher thermal conductivity due to its solid composition and the grouting mortar. Additionally, the vertically varying



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geometry of the window opening results in a reduced thickness of the insulation zone and a higher heat flux density (Fig. 9).

Result

Based on the highest solar radiation profile, a full south-southeast facing (3.00m × 1.80m × 0.75m (h×w×d)) and an adjacent cut building envelope element (1.25m × 0.50m × 0.75m (h×w×d)) from the overall building design were chosen for manufacture as full-scale building envelope elements, aiming to evaluate and showcase the design concept in terms of its manufacturability. Based on the colour code of the solar radiation profile, the self-shading pattern gradually adapts in depth, size, and rotation. Both building envelope elements comply with the initial circular layout, featuring an outer radius of 12m. The cut element primarily served to demonstrate the assembly logic and to validate the tolerance of the proposed building system. Both building envelope elements were manufactured at additive tectonics GmbH within the Big Future Factory (BFF) using a large-scale particle-bed setup with a build space of 4.00m × 2.50m × 0.90m (l×w×h). They were printed in one piece, oriented horizontally, with the front side facing down.

After a total print duration of 9:38:33 hours for the first full building envelope element, the element was lifted in one piece onto an unpacking station, where it cured for four days until it reached its peak hydration temperature. Continuous thermal monitoring was essential to forestall any shrinkage cracks in the green-state element resulting from dehydration. Achieving sufficient green-state strength 24 hours prior to the temperature peak allowed for the excavation of both the structural and the lateral thermal zones. This, in turn, facilitated the placement of the rebar cage, followed by the casting with grouted mortar (Fig. 10).

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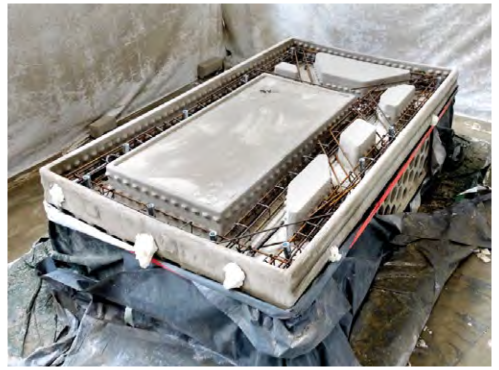
8. Two exemplary results of layerwise 2D heat flux simulations, illustrating the respective heat flux density with resulting U-values of 0.34 W/m²K (Layer 01: left) and 0.83 W/m²K (Layer 06: right). © David Briels / TUM.

9. The use of lightweight aggregates and the customisation of the internal structure aim to significantly improve the thermal properties of the building envelope element to adapt Breuer's building envelope concept to the increased requirements on thermal quality. A separate simulation-based parametric design approach serves to tailor the cellular structure. The used SCA material already provides an improved thermal conductivity of 0.65W/m²K due to the added lightweight aggregates. To improve the insulation properties, one approach pursues the filling of insulation material (e.g., cellulose) after the assembly of the building envelope elements on site. © Julia Fleckenstein / TUM.

10.1

10.2



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11.2

11.3

10. (1) Excavation at the unpacking station after curing. (2) Watering and cleaning of the remaining material. (3) Reinforcement of the lost formwork. © additive tectonics GmbH.

11. (1) Casting grouted mortar with a crane-mounted concrete bucket. (2) Watering and cleaning of the remaining material in the front and post-treatment. (3) Transportation on a semi-trailer and uplifting on site. (1) & (2) © additive tectonics GmbH, (3) © Gerrit Placzek / TUBS.

The grouted mortar was mixed and poured into into a 500l concrete bucket attached to a crane. Then, the material was controlled and poured into the stay-in-place formwork and evenly distributed with a compactor. After 24 hours, the grout had hardened sufficiently to mount a customised supporting steel frame in the structural zone to transmit the tensile forces during the handling processes. After rotating the element in its vertical position, the front side of the element could now be cleaned of the remaining unbound material and made available for post-processing. To guarantee safe transportation, the building envelope element was positioned on a semi-trailer with the structural zone facing downwards to protect the delicate corners of its front side. Upon arrival on site, the element was lifted by a truck-mounted crane and assisted into its vertical position (Fig. 11).

The full building envelope element has a combined weight of roughly 2.2t, out of which approximately 1033.2kg are attributed to the SCA technology, while the remaining weight is distributed among the cast grouted concrete and steel rebar. The cut building envelope element, which was purely fabricated in SCA, weighs approximately 163.2kg (Fig. 12).

Conclusion

The outlined design and manufacturing methods showcase the potential of AMC in replacing intricate, functionally separated multi-layer building systems with customised, functionally hybridised building envelope elements at full building scale (Fig. 1). The building envelope elements not only have the potential to reduce global waste through formwork-free and material-saving manufacturing processes, but also to regulate solar radiation through global shape and local surface customisation. Furthermore, the research validates the approach of using lightweight aggregates within the SCA process and the potential to enhance thermal performance by creating cellular structures filled with blow-in insulation material.

Challenges and potential improvements in the real-scale SCA manufacturing process

The manufacturing of the full-scale SCA building envelope elements encountered significant challenges. The selection of standard Portland Cement as the binder introduced a serious obstacle arising from its inherent tendency to shrink, potentially leading to the formation of shrinkage-induced cracks over time. Additionally, the diverse geometric profiles within the element, combining fast-drying slender sections with slower-drying massive structures, compounded the complexity of addressing potential cracking issues. The downward orientation of the front face and its curvature increased the risk of cracking from unbalanced weight distribution and a tendency to move within the powder bed. This orientation also affected the façade surface quality, as the jetted water tended to penetrate deeper, resulting in dull edges and a reduced resolution. Additionally, during the cleaning and casting process, excessive water leaked through the element and activated previously dry and non-activated layers, causing small imperfections after the full excavation and rotation.

Further research could focus on advancing the Portland Cement material system, especially since the system used in this project was a pioneering development. Larger lightweight particles up to 2mm in size could improve the resulting material performance; these aggregates could displace more cement paste due to their volume and reduced surface area ratio, diminishing the cement matrix for bonding, potentially resulting in a reduced carbon footprint, simplified excavation, and diminished shrinkage and cracking. Moreover, larger lightweight particles could lower the material density while increasing the structural and thermal performance.

Validation of the global shape and local surface design approach

The building envelope elements were set up in Garching in Munich, Germany, oriented in a south-southeast direction. This allowed on-site measurements of the surface temperature over several days in early June 2023. On a warm and sunny day, 6 June, on-site thermal measurements were conducted. Notably, at 12:30, with an average air temperature of 23°C, the measurements revealed a surface temperature difference of 7°C between the self-shaded (lows) and the solar-exposed areas (highs), indicating that the implementation of surface patterns can effectively unlock self-shading properties and lead to a substantial reduction of the surface temperature. Additional shading studies on the same day revealed that the glazed area was shaded in the morning and partially covered in the afternoon. This adjustment was achieved through the shape customisation that evaluated the size and recessed position of the glazed area. However, as a result of structural requirements and the constraints of the built space, the final shape slightly deviated from the initially simulated one.

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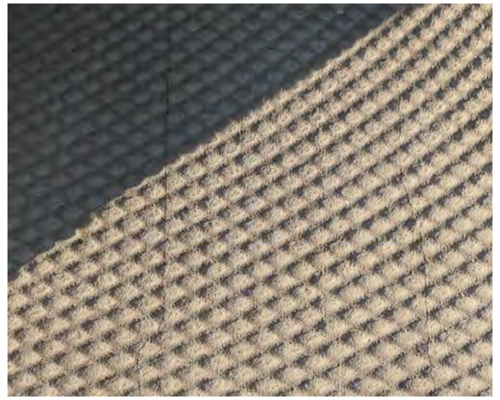

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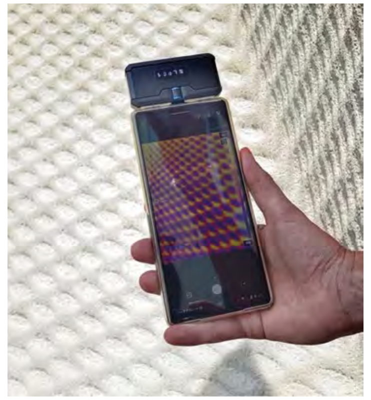

13.2

12. Assembly of the full and the cut building envelope element at the BFF after the post-treatment. © additive tectonics GmbH.

13. (1) Close-up of the self-shading surface geometry on 6 June, 2023, at 19:00 and (2) validation with the infrared thermal camera of the self-shading surface geometry on 6 June, 2023, at 12:30 using a FLIR ONE Pro with an average air temperature of 23°C. (1) © Julia Fleckenstein / TUM, (2) © Janna Vollrath / TUBS.

In summary, the produced elements showed two key potentials: a) controlling solar heat gain through shape customisation helping to reduce energy needed for cooling, and b) controlling solar radiation through local surface customisation. However, to validate and to build upon these findings, long-term monitoring and continued thermal measurements are imperative (Fleckenstein *et al.*, 2023) (Fig. 13).

Hybridising structural and building physical design

In addressing the intricate balance between load-bearing and insulating requirements, the integration and hybridisation of these factors becomes pivotal to achieving a more refined and harmonious design. In pursuit of enhancing structural integrity, advanced simulations with the finite element method would be crucial. This approach would enable precise calculations for the force distribution, accounting for all necessary operational movements, and thereby boosting the efficiency of the printing and casting process. Additionally, employing three-dimensional heat flux simulations enables a comprehensive analysis for both load-bearing and insulating zones, facilitating targeted assumptions to meet both requirements without compromising upon either. Furthermore, including process and handling simulations plays a significant role in identifying potential manufacturing challenges at early design phases, to prevent and address potential for cracking and irregular shrinkage of large-area geometries, and to streamline the transportation and handling processes. Those findings could potentially lead to the segmentation of the building envelope element, along with the development of additional dry-joint assembly methods.

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RESHAPING FABRICATION
A CASE STUDY IN DESIGNING CARBON-REDUCED CONCRETE STRUCTURES

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Introduction

Ambitious climate impact target
As the energy used to operate buildings today trends greener thanks to advances in sustainable energy production, there is a growing interest in the materials used to construct buildings and how the carbon emissions associated with these materials can be reduced. Concrete construction is a significant contributor to carbon emissions, and, with this project, the client, AP Pension, is embarking on a mission to demonstrate a novel approach to reducing the carbon footprint of its concrete buildings.

To encourage this vision, an opportunity to develop and apply innovative design strategies was created by AP Pension in the form of a small community house located in Fredericia, Denmark. The project format made it possible for the project team to engage in a collaborative research process with close coordination between architecture and engineering, the use of computational design to combine geometry with structural analysis, and a 'design through making' mindset with a particular focus on the practical nature of 3D-printed concrete, and how this comes together with the requirements of the Eurocodes and building regulations. This culminated in a series of structural tests, both small-scale in the lab and full-scale at the printing facility, to corroborate the original design assumptions about the material and to validate certain requirements of concrete construction in terms of durability, robustness, and tolerance. As part of the sustainable goals of the project, all parties involved in the project formulated an ambitious project target: to achieve a total CO_2 equivalent below 5kg CO_2/m^2/year over a 50-year period while keeping concrete as the primary material for structural and aesthetic elements.

Carbon reduction strategies
Innovative solutions for design, production, and construction are the driving force behind this project and are essential for achieving the ambitious climate impact goal. Innovative solutions in the project include a thin, double-curved concrete shell roof structure and 3D-printed hollow concrete columns, which strategically only use material where needed.

This geometry optimisation approach is combined with another continuing innovation: low-carbon concrete. By minimising the carbon content of the concrete material

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1. Full-scale testing of printed concrete columns.

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and applying it in conjunction with the minimal material structural forms, low-carbon concrete solutions could be developed.

Geometry optimisation with computational design

The focus of this paper is primarily directed at the 3D printing of the concrete columns. However, it is also interesting to note how computational design tools in general have played a pivotal role in optimising material usage while ensuring structural integrity. Parametric modelling has facilitated the exploration of design alternatives, striking a balance between material efficiency and structural performance – especially in the design of the concrete roof shell and the concrete column layout.

Double-curved concrete shell roof

An ultra-thin concrete shell has been designed as a collaborative exercise between Henning Larsen Architects, who designed the community house, and Rambøll engineers, responsible for the structural design. The engineers have taken advantage of parametric design tools and their ability to provide important structural feedback during the early design stages to suggest an optimal roof design to the architects based on an evaluation of which designs would require the least quantity of material to fulfil the required structural function.

The study includes a form-finding exercise where the optimal form of three different geometries has been identified: a single-curved roof geometry (the bent sheet), a convex double-curved geometry (the saddle), and a concave double-curved geometry (the dome). Based on the structural analysis of the three optimal geometries, the engineers suggested the concave double-curved geometry to the architect. This geometry performed best in terms of minimising deformations and shell stresses, resulting in the slightest thickness and minimal material usage.

The buildability of the dome is ensured through close collaboration with the company Odico A/S, which is developing the formwork for the roof with polystyrene blocks cut to the shape of the dome surface using robotic manufacturing. A small script has been developed by the structural engineers for the formwork company to design a solution using only a minimum amount of polystyrene while achieving the exact shape of the roof structure. This is just one example of how a collaborative design approach has been a necessity because of the innovative nature of the project. Another example is how the buildability of the reinforcement design of the roof has been ensured through detailed 3D modelling of the entire roof reinforcement layout and made accessible to the project contractor.

Column layout

A final optimisation exercise to ensure a thin roof structure has been to define the spans along the edge of the roof geometry by determining the optimal number of columns to support the roof. Meanwhile, the number of columns also influences the size of the loads transferred from the roof to the columns. With a design intention to maintain a similar appearance for each of the columns, an even load distribution is preferable. Hence, an optimisation algorithm was formulated to find the location of the columns that would result in nearly equal loads for all columns.

2. Full-scale print of hollow concrete columns.

3. Interlayer section with horizontal reinforcement. © Danish Technological Institute.

4. Render of the community house project. © Henning Larsen Architects.

As well as supporting the vertical loads, the columns also provide the stability system of the building against lateral loads. The column geometry is such that the rotation of each column about the vertical axis affects the overall lateral stiffness of the structure. Computational design tools have been utilised to identify multiple column layouts where the rotations ensure sufficient lateral stability. These layouts have been presented to the architect, as the rotation of the columns significantly influences the view outside for users of the building.

Hollow 3D-printed columns

In the pursuit of optimising the column geometry, 3D concrete printing has become a central part of the project research. The concrete printing technology aligns with the project mission: building with concrete in a way that reduces the carbon footprint of the building by minimising material use. Hollow 3D-printed concrete columns are a key element of this approach, as they provide the opportunity to harness the geometric advantages of 3D printing with almost total freedom in shaping the columns to only what is required to resist the structural force. While hollow 3D-printed columns present a compelling solution in theory, it is important to note that the technology is relatively novel, especially when applied to structural elements and when used in conjunction with low-carbon concrete. This endeavour combines innovations in design, material science, and construction methods to pioneer a new era of sustainable construction, with 3D-printed columns as an integral component.

Building upon existing 3D concrete printing research

The 3D concrete printing research of the community house project builds upon the knowledge and research available in the field. This includes research on structural performance, design analogies, and the printability of low-carbon concrete. The challenges addressed in prior research on 3D concrete printing laid the foundation for the issues addressed in the community house project in the quest to push the technology and its application to 'real-life' projects further.

The structural performance of 3D-printed concrete has become a subject of significant interest and investigation. This stems from the possibility it presents to create mass-customised structural forms (as opposed to the mass-produced forms used at present), allowing designers to optimise the use of material and reduce the carbon content of the structure without significant increases in cost or time. As we endeavour to push the boundaries of 3D concrete printing towards sustainability and structural viability, it is pertinent to address structural performance issues and the available reinforcement options. However, moving into that area of research, the basis of experience is limited. Notably, in 'The realities of additively manufactured concrete structures in practice', Bos *et al.* (2022) state that many 3D concrete printing projects do not utilise the technology for primary load-bearing purposes, primarily because of limited reinforcement options and regulatory obstacles.

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Freund and Lowke (2022) discuss the integration of horizontal reinforcement as a prerequisite for many structural elements in 3D concrete printing. The paper points out that, although several additive manufacturing techniques rely on unreinforced concrete, reinforcement is indispensable for many structural applications.
A promising reinforcement strategy for structural elements involves the use of interlayer reinforcement, meaning applying horizontal reinforcement between the printed layers, capitalising on the layered characteristic of the additive manufacturing process.

With the ambition to print load-bearing and stabilising structures, horizontal reinforcement plays a vital role in the community house project. Consequently, the same approach is adopted by integrating horizontal reinforcement in the form of small-diameter steel reinforcement bars between layers to meet the need for horizontal reinforcement. This approach ensures that our printed structures can effectively withstand horizontal wind loads and resist the temperature loads they are exposed to when situated outside the building envelope, which was a requirement of the architecture.

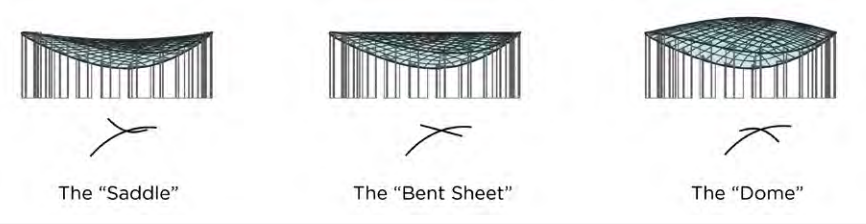
Design analogies

The feasibility of applying vertical reinforcement to printed structures is virtually unattainable as a result of the inherent characteristics of the printing technique. To address this limitation, a post-tensioning system is devised for the hollow printed columns, ensuring that the columns consistently remain in compression. This approach bears similarities to the approach used in a few instances of projects employing 3D concrete printing for primary load-bearing structures, as discussed by Bos *et al*. (2022). Nevertheless, it is essential to underscore the methodological differences. Instead of relying on analogies with unreinforced masonry, as is the case for the discussed projects, the design of structures for the community house conforms to established concrete codes and standards, treating the printed material as reinforced concrete. This approach entails extensive testing to confirm that the 3D-printed material for the community house project performs equivalently to conventional reinforced concrete.

Printability with low-carbon concrete

In contrast to many other printed projects that primarily use concrete mortar to enhance flow and visual quality, this project adheres to concrete code standards by employing concrete with large aggregates (8mm), a fundamental requirement of the Eurocode. The concrete mixture is carefully designed to meet both code specifications and the constraints associated with the 3D-printing technique, while also reducing embodied carbon. This innovative approach to concrete mix design aligns with the overarching goal of achieving sustainability in concrete construction. However, the combination of low-carbon concrete, adherence to Eurocode concrete standards, and the 3D-printing process comes with its own set of challenges.

In the context of 3D concrete printing, green concrete formulations often incorporate supplementary cementitious materials (SCMs) and recycled aggregates, noticeably affecting the workability and printability of the material (da Silva and Kaasgaard, 2022). Achieving the correct mix design that balances sustainability with 3D-printing feasibility is a complex task. Addressing this requires in-depth research and development efforts to create green concrete mixtures optimised for 3D printing. The customised mix design for the 3D-printed hollow columns in the community house project was developed by experts at the Danish Technological Institute in collaboration with concrete supplier Unicon and the printing companies COBOD International A/S and 3DCP Group A/S.



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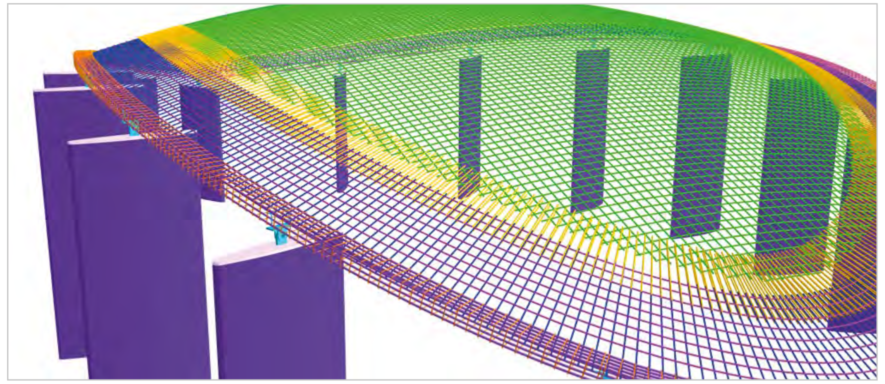

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5. Three optimised geometries for the concrete roof shell.

6. Reinforcement model of the concrete roof shell.

7. Mortar print mix versus concrete print mix. © Danish Technological Institute.

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8. Application of horizontal reinforcement to the full-scale column print.

9. Printed concrete column mockups for compressive testing.

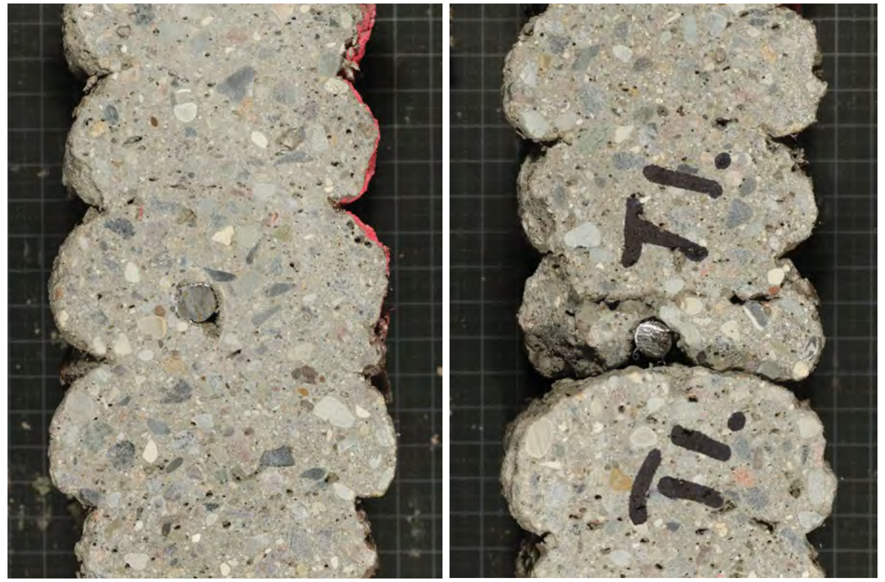
Incorporating SCMs and reducing cement content, while environmentally beneficial, may extend curing and setting times. This not only affects the speed of 3D printing but also the structural integrity of the final product. Striking a balance between sustainability and expedient production is crucial and necessitates comprehensive testing. A suitable test programme was formulated by Rambøll, and the testing and analysis of the test results have been carried out by the Danish Technological Institute. The programme included structural tests for compression, buckling, shear, and punching, as well as tests on the durability of the concrete. For the most part, these were carried out on small-scale specimens in the lab. However, full-scale destructive tests were also carried out in the concrete printing facility to measure and observe the global behaviour of the columns and test the jacking process.

Results and achievements

Method and structural validation

The exploration of 3D concrete printing has been integral to the project's pursuit of sustainable fabrication practices. To ensure the structural integrity and performance of the 3D-printed elements, a combination of research, analysis, and physical testing has been conducted. These efforts aim to validate the structural capabilities of the printed elements and offer valuable insights to inform design iterations and adjustments, ultimately leading to an efficient and resilient structure. This method is illustrated through a design information map.

To date, the Danish Technological Institute has performed a series of tests on material and component levels, and at full scale. Overall, the test results have verified a strength



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significantly higher than the design value and no stability issues have been identified in the full-scale testing. Also on a material level, the mix design has shown promising results except for some concerns related to frost resistance. However, it was necessary to conduct additional inspections to assess the quality of the casting technique, as described in the following section.

Quality inspection by the Danish Technological Institute
The Danish Technological Institute has performed a micro-analysis aimed at characterising and quantifying casting defects in 3D-printed concrete sourced from the community house project. The investigation involved visually inspecting four longitudinal cut slices, each measuring 15-20cm in width and approximately 1m in height, oriented perpendicular to the column's exterior. Defects can be categorised as follows: poor *concrete compaction* leading to air pockets, poor placement of the reinforcement resulting in loss of *concrete cover*, or poor *bonding between concrete and rebar*. The conclusion to the analysis of possible defects is gathered in the sections below.

Concrete compaction: The analysis revealed that the individual print layers forming the column adhere well to each other. Some elongated air inclusions exist between layers but are not deemed significantly detrimental to durability or strength. Overall, the concrete exhibits few air inclusions and is well compacted.

Concrete cover: Detrimental conditions affecting concrete durability and construction strength include inadequate concrete embedment of rebars, the presence of certain air inclusions near the surface of the column, and thin cover thickness of rebars on the inner side, typically not exceeding 20mm.

Reinforcement-concrete bond: A notable issue concerning the rebars is that the concrete used in 3D printing fails to flow and embed the rebars effectively after placement. The subsequent print layer tends to bend around the rebar rather than envelop it, resulting in poor embedment, loose rebars, and the formation of larger encapsulated air voids around the rebars. Consequently, the composite action of concrete and reinforcement steel working together is not achieved, and the 3D-printed material is unsuccessful in performing equivalently to conventional reinforced concrete.

Conclusion

In this case study, the potential of reshaping conventional fabrication practices to achieve meaningful carbon reduction in concrete structures has been explored. Through interdisciplinary collaboration, computational design, and a 'design through making' mindset, the study has demonstrated how these innovative approaches can advance the industry's response to environmental concerns.

It is essential to recognise that 3D concrete printing technology and its structural applications are evolving rapidly. While the study has uncovered certain critical pitfalls, it should be emphasised that challenges are inherent to pioneering novel technologies. Innovation and development in 3D concrete printing are underway, and future iterations of this technology are anticipated to overcome many of the issues encountered. As for now, the structural performance and printability of low-carbon concrete are indeed complex topics, and it is undeniably exacting to combine the two successfully in practice. To fully understand their potential carbon savings, further research is required to provide tangible data. As the industry moves forward, future investigations can hopefully build upon these findings and find a way to combine low-carbon concrete with the printing technology and the material reduction potential that the method entails.

As the project remains in the design and testing phase, and the design has not yet been finalised, it cannot be concluded with certainty whether the project target of achieving a total CO_2 equivalent below 5 kg CO_2/m^2/year over a 50-year period will be met. The most recent life cycle assessment (LCA) analysis does, however, imply that the final numbers will certainly be close to the target.

10. Longitudinal cut slices from quality inspection. © Danish Technological Institute.

11 & 12. Printed concrete cylinder following destructive test. © Danish Technological Institute.

13. Shear strength testing of the printed concrete element. © Danish Technological Institute.

14. Compressive testing of the printed concrete column mockup. © Danish Technological Institute.

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SUEÑOS CON TIERRA/CONCRETO
MULTI-MATERIAL FABRICATION FOR LOW-CARBON CONSTRUCTION – AN OPTIMISED FLOOR SYSTEM FOR AFFORDABLE HOUSING IN MEXICO

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This work addresses the global need for affordable housing construction through a contextualised approach to materially efficient design and fabrication of building systems. Mexico is one of the most urbanised countries in the Global South, facing a rapidly increasing population and a considerable percentage of inadequate housing (URBANET 2019). In 2016, it was estimated that 40% of all private residences in Mexico were considered inadequate, according to UN-Habitat (2018), both in terms of living conditions and structural/seismic integrity. Informal housing comprises more than half of all housing construction in Mexico, disproportionately affecting the most vulnerable segments of the population. In collaboration with local partners in Mexico, a novel structural floor system was designed and fabricated to use approximately half the material of conventionally available building products, with the aim of substantially reducing the economic and environmental costs of affordable housing construction.

This prototype combines widely available low-carbon earthen block technology (EcoBlock) with a materially efficient, code-compliant beam and block floor system fabricated entirely in Mexico. Shape-optimised, reinforced concrete beams are produced in reusable fibreglass moulds, while mass-customised spanning blocks are 3D-printed in a local architectural ceramic material. The floor system is then conventionally assembled using existing construction methods. The *Sueños Con Tierra/ Concreto* Pavilion, which, shortly after installation, survived a magnitude 6.8 earthquake, demonstrates how our hybrid digital fabrication method can provide adequate and safe housing without jeopardising the country's commitment to sustainability.

Introduction

The global demand for housing is projected to double by 2060, necessitating the development of lower-cost, low-carbon and quick-to-scale construction innovations (UN GSRBC, 2021). In multi-storey buildings, between 60 and 80% of the structural mass and embodied carbon is found in horizontally spanning elements such as floor slabs (Huberman *et al.*, 2015; De Wolf *et al.*, 2016; Foraboschi *et al.*, 2014). As a result of the relatively high cost of industrial building materials, many affordable housing projects in Mexico utilise the beam and block system for horizontal spanning elements. The construction method uses precast concrete beams with blocks (typically concrete, XPS, or other low-strength materials) that span

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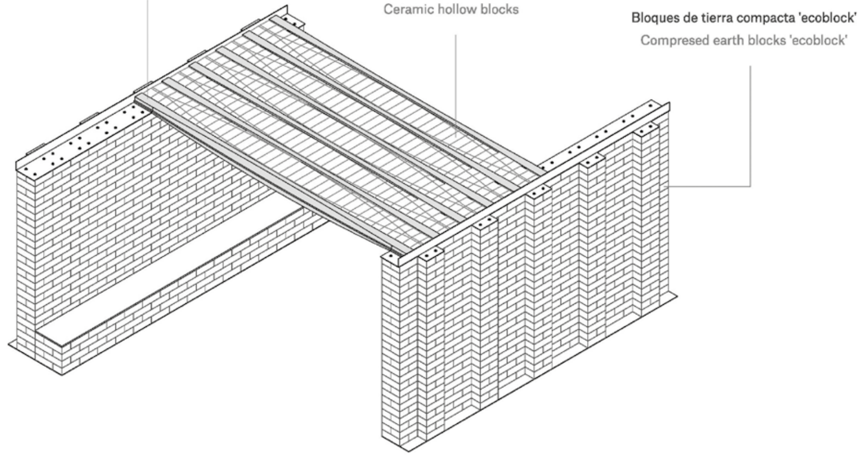
between the beams to provide lost formwork for a cast-in-place slab. This technology has been in use for decades and is popular in Mexico because it relies on lightweight precast units, eliminating the need for on-site shoring and large machinery. However, the existing system prioritises ease of fabrication at the expense of material efficiency, offering considerable opportunities to reduce material consumption and carbon emissions.

This project presents a strategy for reducing the costs and embodied carbon of the beam and block system by minimising material through emerging methods in shaped structural design and digital fabrication (Ismail *et al.*, 2021; Curth *et al.*, 2020; Gascón Alvarez *et al.*, 2023). In contrast with the uniform, extruded geometry of the conventional beam and block system, this design introduces a highly efficient alternative, where material savings are possible due to the precise, sculptural shaping of reinforced concrete beam elements. The resulting curved geometries create varying conditions for the spanning block elements along the beams' lengths, posing a challenge for typical mould-based manufacturing paradigms. Instead, 3D printing is utilised to achieve geometric customisation in a traditional, local material.

The design and construction processes were developed with New Story and ÉCHALE, two local partners developing low-cost, equitable, and sustainable housing in Mexico, and the Leventhal Center for Advanced Urbanism at MIT. The resulting prototype (*Sueños Con Tierra/Concreto*) was installed as part of the annual Mextrópoli Architecture and City Festival to showcase a prospective pathway towards sustainable housing in Mexico using low-carbon materials and building techniques that already exist in local construction practice and building code. Fabricated using lightweight precast beams cast in fibreglass moulds and 3D-printed blocks made with locally sourced clay, the shape-optimised beam and block system has a total embodied carbon nearly half that of existing products (as calculated using material take-offs and cradle-to-gate embodied carbon coefficients). The bearing walls are assembled by post-tensioning 'EcoBlock', compressed earth blocks produced by ÉCHALE with local soil and stabilised with small quantities of cement. The pavilion was designed to meet ACI 318 requirements for structural reinforced concrete, which is accepted for Mexican housing construction. This paper offers a description of and insights into the integrated design–engineering–fabrication computational framework that technologically enabled the project, along with reflections on the collaborations with local experts in the project's context.



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Parametric-shaped floor system

The design of the *Sueños Con Tierra/Concreto* prototype was driven by a fabrication and material-aware optimisation model. Beginning with a systematic review of local standards and common *vigueta y bovedilla* building practices, particularly the typical affordable housing design employed by ÉCHALE, shape-optimised beam and block geometry was an output from a flexible parametric model. The shaped beams were structurally optimised using a previously published method developed by the authors (Ismail and Mueller, 2021), which combines a parameterised boundary representation of beam geometry with detailed constraint checking of code-based shear and flexural reinforced concrete engineering limits at cross-sections along the length. The shape of the beam is found through a constrained gradient-based optimisation solver. The method can adapt to different manufacturing and mould technologies through the parameterisation of the bounding geometry or through additional constraints (e.g., zero, single, or double curvature, valid tool pathing, etc.). The optimisation objective is to minimise embodied carbon in this project, but the method can similarly be used to minimise cost, mass, or other measurable targets.

In this project, the existing beam optimisation method was extended to incorporate the design of the ceramic block and the interaction between the parts of the system. Considerations were taken to account for the weight and spacing of each beam element to ensure the system could be assembled safely by two workers. Details of the interface

1 & 4. Shaped, reinforced concrete beams are paired with mass-customised ceramic blocks to form a materially efficient yet conventionally assembled construction system.

2. By combining common construction methods with emerging parametric structural design and 3D printing technology, we can significantly reduce the carbon impact of residential construction in Mexico.

3. Combining a generalised design optimisation workflow with building codes and local material properties facilitates a direct-to-production engineering process.

5. The completed floor system achieved a nearly 50% reduction in carbon emissions compared with conventional beam and block products through novel shape optimisation methods. While reminiscent of the traditional beam and block system, the resulting aesthetic speaks to the prototype's lightness and modern fabrication methods.
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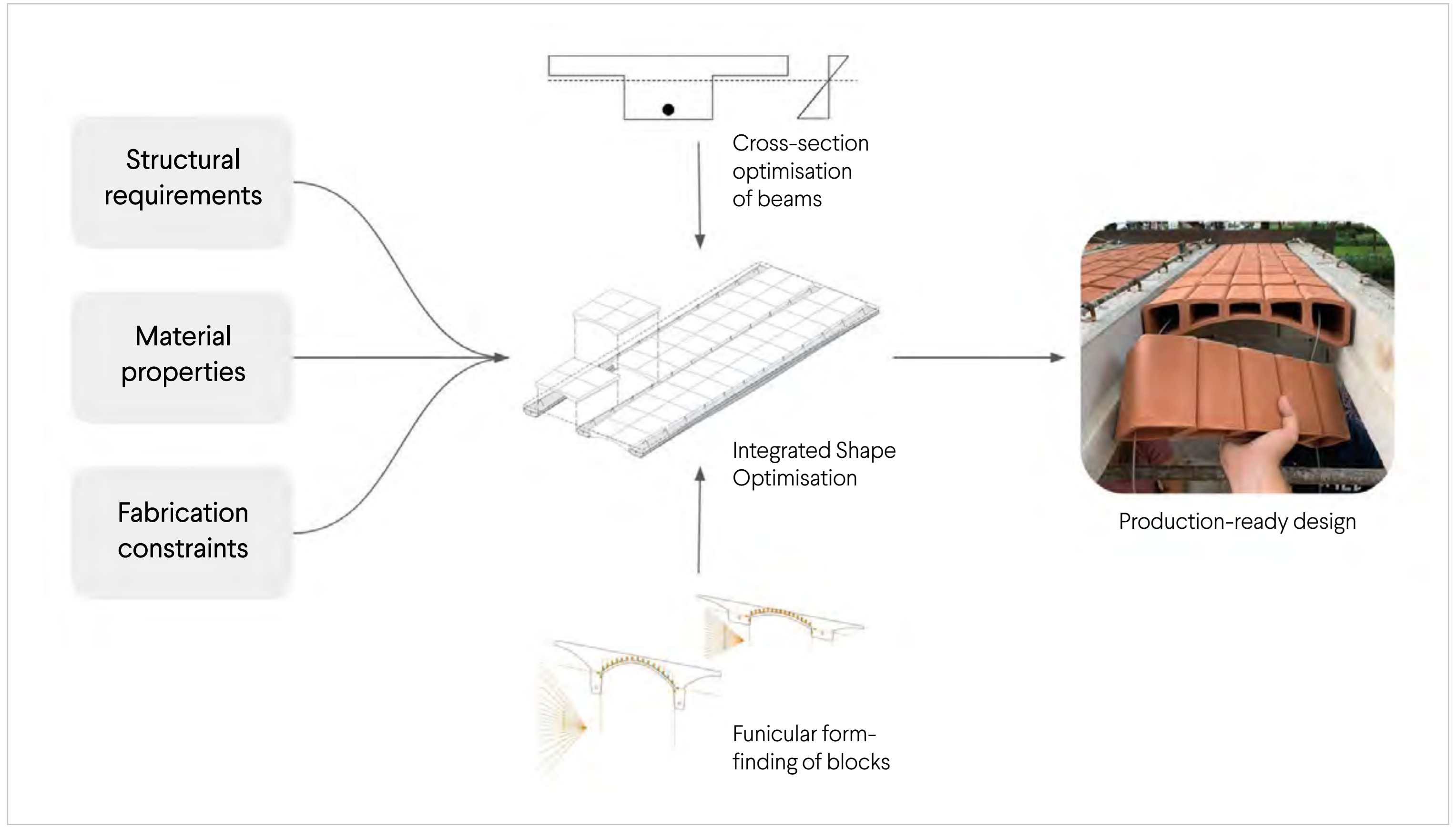

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between beam and block (Fig. 10) were driven by the geometric constraints and predicted tolerances of the concrete casting and ceramic 3D-printing processes. The printed ceramic blocks were structurally modelled using graphic statics to validate that the internal thrust line generated by the weight of the wet concrete topping slab could be supported in pure compression (Fig. 3). Detailed drawings and 3D models were supplied to the local manufacturing partners, allowing them to leverage their individual expertise to produce the elements to a high standard of precision in approximately two months from contract to delivery.

The mould-making methodology for the shaped beams was multi-step, involving CNC blocks of wood glued together and then carefully hand-sanded to produce a positive of the shaped beam. This process allowed for precise, doubly curved surfaces to be matched from 2D section cuts of the beam design. The resultant two-part mould (Fig. 6) can be reused up to 200 times (according to the manufacturer) to mass-produce shaped T-beams for a set span – in this case, 4m. The beams themselves were designed to use 30MPa concrete and 415MPa longitudinal and shear reinforcement, which are typical, widely available materials for these systems in Mexico. The beam utilises a single 10mm diameter longitudinal section of steel rebar and 8mm shear reinforcement. The completed T-beam system with cast-in-place topping slab is engineered to code-compliant design loads; however, the precast beams themselves are the minimum depth required to resist the dead load of the elements themselves prior to casting, creating a highly materially efficient complete floor system.

The additive manufacturing (AM) process, on the other hand, involved no drawings, only the direct exchange of machine code from our design team to the robotic fabricator. The 3D-printed ceramic blocks were designed to an assumed strength of 1.5MPa using a mixture of clay from Oaxaca and Zacatecas common in the production of architectural tile and brick and validated through a simple deadweight load test on site. The water content of the clay was adjusted to facilitate printing, and shrinkage was calibrated into the digital model based on printed and fired samples. Large batches of clay were then prepared by hand with a ceramic dinnerware manufacturer in Mexico City, Anfora Studio. Formulating a high sand content clay and uniform drying conditions was essential to minimising shrinkage and warping of the final blocks. Multiple prototypes of the block were produced in research facilities in the US and Mexico to ensure the block toolpath balanced print speed, consistent layer adhesion, and seams that did not interfere with either the visible arch of the block or the critical supporting corners, which would interface with the concrete beams. The combined, hybrid nature of the resulting structure points to both the great potential of digital fabrication and the challenges related to its integration into the largely manual world of construction.

6 & 7. A reusable, two-part fibreglass mould was manufactured with a local partner to produce beams that can be installed comfortably by two builders. A two-part mould was necessary to incorporate the shelves for spanning ceramic blocks.

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Cost Item	Cost (USD)
Contractor + EcoBlock walls	26,754.00
Clay blocks - materials	750.00
Clay blocks - labour	18,900.00
Fibreglass moulds - materials + labour	8,650.26
Other	3,132.24
Total cost	**58,186.50**
Cost/m²	**2,424.44**

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While the precast beams and bearing walls were fabricated with methods readily available in Mexico, the 3D-printed *bovedillas* are the most experimental features of the pavilion and were, consequently, the most expensive elements (Fig. 11). Further efforts can be made to reduce the cost of the 3D-printed blocks, such as using simpler 3-axis systems holding multiple clay extruders to speed up printing, using continuous flow pumps to simplify material delivery, and using larger kilns to improve the efficiency of the firing process. Such advancements borrow from standardised ceramic processes and could drastically improve the viability of 3D printing custom blocks for the shaped beam and block system. Of note was the availability of large-scale rapid prototyping in an experimental material as a service in Mexico City. As AM for architecture becomes a more widespread practice, access to local fabricators with extensive expertise is growing.

The *Sueños Con Tierra/Concreto* Pavilion

The *Sueños Con Tierra/Concreto* prototype was a successful deployment of a hybrid digital fabrication system with local partners. Over the course of a week, the wall and floor systems were assembled to the expected tolerance without the need for any heavy equipment or machinery beyond hand tools and scaffolding (Figs. 7, 12). No foundation was constructed. Instead, the post-tensioned walls held the floor system in place for the duration of the temporary installation. The resultant prototype not only met local building safety requirements but reduced the carbon footprint of a conventional floor system by 50%. By working entirely with local manufacturers to produce the elements of the pavilion, we demonstrated the potential to deploy a parametric optimisation design tool with readily available materials and fabrication capabilities. Through rapid iteration and open communication with our partners, we were able to drastically improve a common system's material efficiency without compromising its performance.

An accounting of project costs illustrates how even novel and largely experimental fabrication strategies could be used to produce a first full-scale prototype at a relatively low cost. The beam moulds are particularly notable, given the potential to reuse them up to 200 times. AM of the ceramic blocks was costly largely due to labour in setting up the clay processing and printing system. Travel costs for the team developing the floor system are also factored into the prototype budget.

8. With proper material preparation, a locally sourced clay mixture can be calibrated for high-tolerance-production additive manufacturing.

9. Production of the blocks (*bovedillas*) at Manufactura, a digital fabrication studio based in Mexico City. Layers of clay are robotically extruded and then fired before they are transported to site. Additive manufacturing of 3D-printed ceramic blocks could be scaled through additional extruders and robotic systems, as is common in the automotive industry.

10. The geometry of the 3D-printed ceramic blocks is precisely tuned to span between beams that vary in depth and width to minimise material consumption and emissions associated with both elements.

11. A cost breakdown of the as-built pavilion is a limited but critical indicator of the viability of scaling the elements of the proposed floor system.

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Discussion

During the two-week Mextrópoli exhibition in Mexico City, the pavilion was visited by thousands of people, both local citizens and tourists. The installation provoked visitors to imagine a future for Mexico City, and their collective dreams were displayed (Fig. 15). Anecdotally, visitors shared that they understood the connection of the shaped beam and block system to its traditional predecessor and saw it as an aesthetically pleasing advancement to a tried and true construction method. The system itself was well received by the contractors assembling the structure, establishing a critical and tangible link between academic digital fabrication research and the practical realities of building low-cost, low-carbon housing. The experiential prototype provided critical insight into reducing climate impact in the Mexican construction context for designers, builders, and citizens, while opening a path for future research exploration.

Future work

To broaden the impact of the shape-optimised beam and block system, further studies could be conducted to reduce production costs through scaling manufacturing processes. In addition, a version of the system complete with a topping slab could be put through load testing to further validate its feasibility. The 3D-printed ceramic blocks could also undergo testing to ensure the consistency and strength of the elements with various locally available clays and firing processes across Mexico. To embed further functionality and reduce the embodied carbon of buildings made with the system, a study of the potential for thermal optimisation of the ribbed slab and hollow blocks could be explored based on prior research (Gascón Alvarez *et al.*, 2021).. As of this writing, the beam and block prototype produced for Mextrópoli is being used as the basis for the development of certified and readily available shape-optimised floor systems with industrial manufacturers in northern Mexico. The project's future will be applying the validated material and fabrication-aware design methodology to other contexts with differing building codes and structural requirements.

12. Compressed, sun-dried blocks fabricated with *tepetate* (a local soil with high contents of clay) were assembled with a series of post-tensioned rods that facilitated the assembling and disassembling process for a stable dry fit construction.

13. The system results in an array of one-way-spanning T-beams with shaped clay blocks acting as lost formwork and a continuous concrete diaphragm on top. The latter was not cast during the exhibition for disassembly purposes.

14. The prototype was installed for two weeks in Plaza de la Alameda in Mexico City and featured in the Mextrópoli Architecture and City Festival in September 2022. © Walter Shintani.

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15. An interactive exhibition panel, designed in collaboration with the Leventhal Center for Advanced Urbanism at MIT, asked visitors to write their thoughts on multiple issues concerning Mexico City, such as transportation, housing, or access to water. © Walter Shintani.

Acknowledgements

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LUNARK
DESIGN AND FABRICATION OF AN ORIGAMI-INSPIRED DEPLOYABLE LUNAR HABITAT PROTOTYPE

KARL-JOHAN SØRENSEN / SEBASTIAN ARISTOTELIS
SAGA SPACE ARCHITECTS

Introduction and overview

The harsh constraints imposed by the Lunar environment necessitate efficient, autonomous, and self-sufficient structures for human habitation (Benaroya and Bernold, 2008). Innovations in space architecture, characterised by lightweight, durable, and resource-efficient design solutions, provide valuable insights for tackling similar challenges on Earth related to resource scarcity and climate change.

This paper describes the design and fabrication of the LUNARK habitat: a deployable Moon habitat prototype which was field-tested during an analogue Lunar mission in northern Greenland in the fall of 2020. The habitat was designed and constructed by SAGA Space Architects and a team of volunteers at the betaFACTORY workshop in Copenhagen, Denmark. The habitat autonomously sustained two analogue astronauts over the 60-day span of the mission, 1000km north of the polar circle. The mission underscored the potential of compact and efficient off-grid dwellings for extreme environments on Earth and beyond.

The habitat's defining feature is its origami shell, which can expand by approximately 700%. To achieve this transformation, our design process involved a parametric geometric workflow, multi-objective optimisation, and physics-based simulations. In this paper, we introduce a geometric formulation for creating closed, foldable origami spheres, adding to the emerging field of rigid thick origami architecture. Using origami allowed us to design a structure that met compact transportation requirements while maximising the expanded volume.

The construction of the habitat utilised an integrated digital fabrication workflow, allowing for the complete in-house production of the habitat. Throughout the fabrication, various challenges arose and were addressed, offering insights into translating a complex geometric concept into physicality.

The habitat featured a structural aluminium frame, a carbon-fibre origami envelope clad with solar panels, recycled PET insulation, flexible composite rubber seams, and a basic life support system. The interior was divided into two levels to house sleeping pods, a multi-purpose area, an airlock/wetroom, and utility storage.

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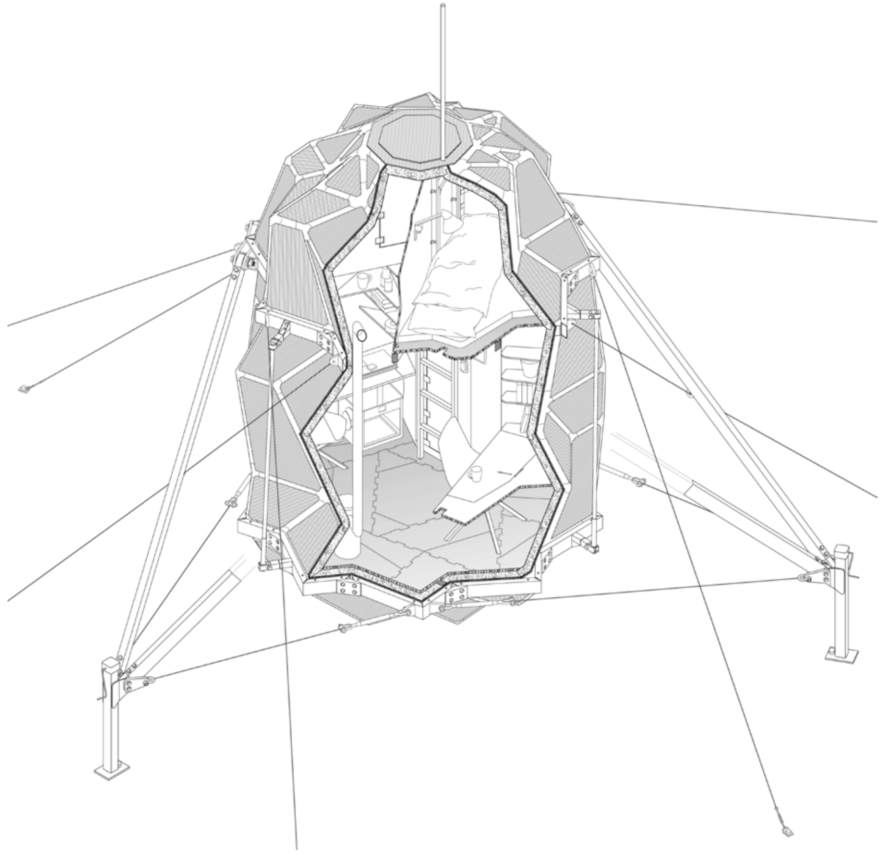
1. The LUNARK habitat.
© Karl-Johan Sørensen, Sebastian Aristotelis, SAGA Space Architects.

Background
While origami has provoked considerable interest across various design and engineering disciplines, research on architectural-scale origami structures, particularly those employing curved Miura-ori tessellations, remains relatively underdeveloped (Zimmermann *et al.*, 2021). This is likely due to the inherent complexity of designing and constructing closed polyhedral origami tessellations (Melancon *et al.*, 2021). Furthermore, no one has demonstrated a functional origami building for space or Earth. Hence, we propose an alternative to inflatable space habitats, utilising a rigid, deployable origami shell, capitalising on the structural integrity and hardware-interfacing benefits afforded by rigid plate assemblies.

Description of the habitat

The habitat was designed with the constraint of being deployable by a team of two in an extreme environment without any external help or infrastructure. Consequently, both the legs and interiors can be easily dismounted, allowing the origami shell to be folded and rolled into a shipping container for transport to and from the site. The envelope is a fully closed rigid origami shell made of rigid foam carbon-fibre sandwich panels, with a flexible rubber-ply composite seam at the edges. The shell is clad with solar panels, providing a total capacity of 1000 watts. Supporting the shell is an integrated structural aluminium frame, which folds simultaneously with the rest of the shell. The frame is divided into three aluminium truss legs and two structural rings connected by columns, which also support the floors. The habitat rests on three jack-feet and is anchored to the ground using nine steel wires to manage lateral wind loads.

The habitat's interior is insulated with 64mm ArmaFlex Ultima insulation — installed post-deployment using Velcro. The internal volume is partitioned into one and a half inhabited floors and a separate utility space. The 4.5m^2 main floor comprises the airlock/bathroom and the primary living and working area. Situated within the lower hemisphere is the utility space, featuring water storage, waste management, batteries, and equipment. The upper hemisphere contains two private sleeping pods and the emergency exit. The habitat only has one window located in the airlock. On the Moon, windows should be avoided because of their inability to sufficiently shield against cosmic background radiation and charged particles from solar storms (Narici *et al.*, 2018). Furthermore, windows can cause stress concentrations in the shell. To address the absence of natural light, we developed and installed a circadian light system in every room. This system autonomously cycles through randomly generated



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artificial sunlight patterns that mimic the frequencies of atmospherically filtered sunlight as it hits the Earth's surface, thus providing a pseudo-natural daylight experience that closely resembles the subtle hourly variations of natural daylight on Earth. Heating is facilitated through a standard petroleum boat oven, and electricity is sourced from the solar panels.

Designing the origami shell

We started with defining our design constraints based on planned near-future crewed lunar missions, such as NASA's Artemis missions (Creech *et al.*, 2022):

1. Two people should be able to inhabit the habitat for two months, self-sufficiently.
2. The habitat should fit in a modern rocket fairing.
3. The envelope should be a pressurisable solid (i.e., not a box).
4. The habitat should withstand the arctic environment.
5. Deployment should be straightforward and necessitate minimal manual assembly.

2. Cut-away axonometric drawing of the LUNARK habitat. © Karl-Johan Sørensen, Sebastian Aristotelis, SAGA Space Architects.

3. The main living space. © Karl-Johan Sørensen, Sebastian Aristotelis, SAGA Space Architects.

4. The main living space from above. © Karl-Johan Sørensen, Sebastian Aristotelis, SAGA Space Architects.

5. Geometric origami definition steps 1-6. © Karl-Johan Sørensen, Sebastian Aristotelis, SAGA Space Architects.

6. Geometric origami definition steps 7-9. © Karl-Johan Sørensen, Sebastian Aristotelis, SAGA Space Architects.

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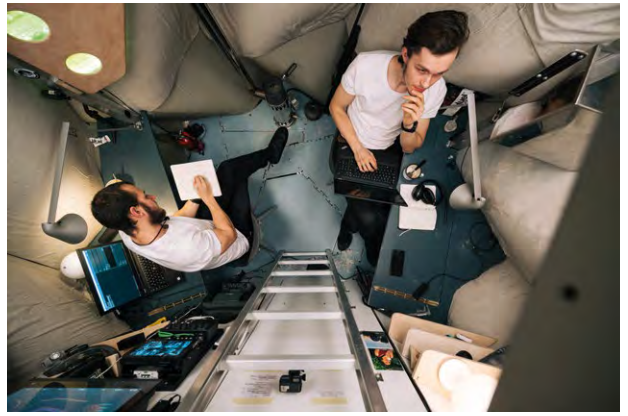

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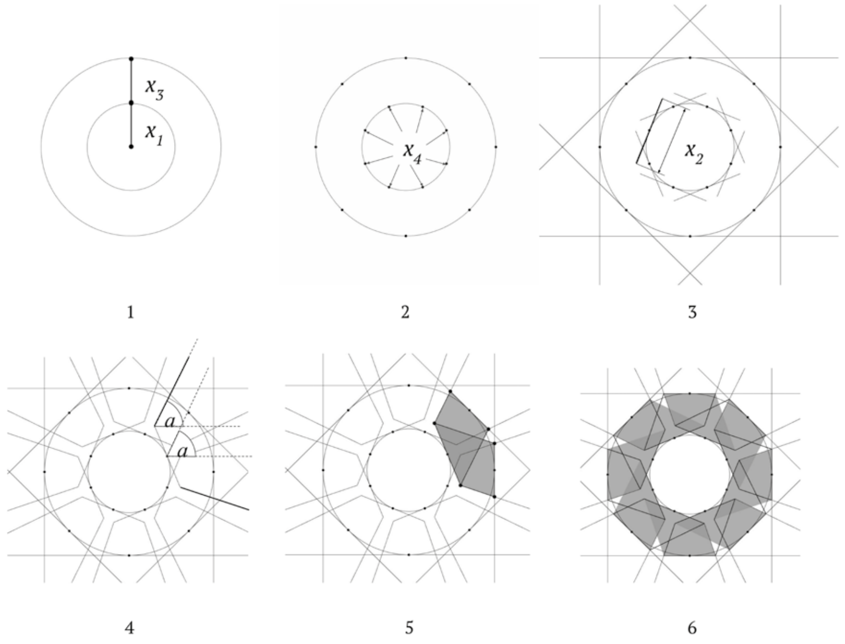
Upon investigating the state of the art in deployable closed structures, we identified origami as an ideal candidate to meet these constraints. Compared with telescopic and inflatable concepts, flat, rigid origami panels offer superior stiffness and simplify the integration of hardware, such as solar panels, which are generally not flexible enough to fold with an inflatable membrane (Badagavi *et al.*, 2017).

The tessellation of the shell draws from the flat Miura-ori pattern, named after its inventor, Kōryō Miura, a Japanese astrophysicist (Miura, 2009). We selected this pattern for its capability for bidirectional expansion, ensuring that a surface retains its overall geometry throughout the folding process. An essential aspect of this research was formulating the parameterised geometric definition for a constructible closed spherical origami envelope.

Geometric origami formulation
The conventional method for parameterising Miura-ori utilises a four-panel base unit. By adjusting the angles of the reverse folds from one row to the next, we can introduce curvature to the sheet. However, this approach



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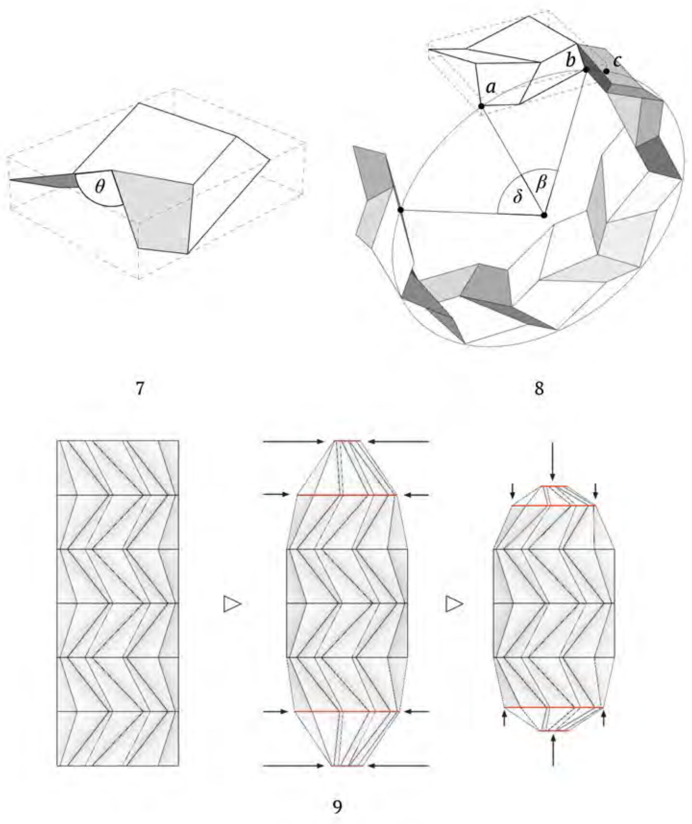

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presents challenges: the exact curvature becomes difficult to regulate, resulting in excessive deformation during folding. To address this, we propose a novel method for parameterising Miura cylinders, wherein the folded cylinder itself serves as the starting point. This technique guarantees that the derived cylinder will fold flat while maintaining a sealed seam. Such a folded cylinder can be described by just five variables, $x_1 ... x_5$. The following geometric steps construct the origami cylinder:

1. Two concentric circles are drawn, defined by an inner circle radius x_1 and an outer circle offset x_3.
2. The circles are divided into n segments, as defined by x_4.
3. Tangent lines are drawn at each point. The inner line is defined by x_2, and the outer line extends infinitely.
4. Lines are drawn from the endpoints of the inner lines at an angle α, which is equal to the angle between the two points.
5. Now, the intersections of these guidelines are used to define two of the four parallelograms that make up a single Miura cell.
6. Arraying the Miura cell completes the folded cylinder.
7. The geometry of a folded cell can be derived solely from an angle θ. This is a consequence of the Miura origami having only one degree of freedom.
8. A circle is drawn through projected points a, b, and c, and the angle β is used to array the Miura cells around this circle.
9. Using a bisecting search, we find an angle θ that minimises δ, thus closing the cylinder seam. This ring is then arrayed n times, as defined by the final design variable x_5 to form the complete cylinder.
10. Scaling the horizontal edges of the cylinder and moving them vertically creates the final spherical design.

The parametric definition leads to numerous design variations. We applied an evolutionary optimisation algorithm to find a design vector that minimised deformation during folding while maximising expanded volume. Following this, we conducted a physics-based folding simulation with Kangaroo3d to verify its foldability. Throughout the geometric development process, folding simulations were cross-referenced with 3D-printed prototypes to ensure the accuracy of the simulation outcomes. A QR code is included for readers to access animations and videos of the origami development.

The maximum expanded volume of the final origami design, as constrained by the dimensions of the folded state inside the container, was $17.5m^3$, and the floor area of the main space was a mere $4.5m^2$. These constraints necessitated careful consideration of the subdivision and programming of the interior space. So, before detailing the mission-ready habitat, we constructed a static 1:1 plywood mock up of the shell to ensure liveability and facilitate rapid iterations of the interior divisions of the volume.

From origami concept to buildable structure

Transitioning from the origami concept to the detailed design involved extensive design iterations, construction of scale prototypes, material testing, structural analysis, and finite element method (FEM) simulations on the shell and frame. With each new insight gained, we added to a comprehensive master model of the habitat in Rhino 3D. This model encompassed all geometric aspects, the bill of materials, fabrication specifications, generated CNC toolpaths, and fabrication drawings.

Shell

The origami shell had to withstand significant lateral loads as a result of the high winds on the site, known for some of the strongest winds in the world (Tollinger *et al.*, 2019). Regrettably, there were few precedent examples of origami constructions, necessitating the development of our own solutions. Our initial focus was on selecting suitable materials for the shell. We established criteria for the panels, prioritising lightness, strength, and rigidity, while the flexible seam required strength and flexure. Consequently, we opted for carbon-fibre sandwich panels with a rigid foam core composed of 100% recycled PET for the rigid panels. For the flexible seams, we utilised a rubber-ply composite, typically used to make industrial conveyor belts.

Using a parametric definition in Grasshopper 3D, we discretised the seams into edge bands and node patches, and the panels were offset from the edges and filleted to create the fabrication geometry. Approximately 4000 bolted connections, spaced 8cm apart, secured the seams to the panels, and silicon was used at the carbon-fibre–rubber interface to ensure waterproofing. We conducted a deflection analysis for each panel under maximum wind pressure using Abacus FEM. The results demonstrated that the flexible seam effectively distributed stresses across the shell, with each panel experiencing a maximum deflection of 1.5mm under the highest wind pressure. Physical fracture testing was done on material assemblies such as the seam–carbon-fibre connection and glued joints. The critical materials were cryo-tested at -50C° in an industrial freezer at a nearby meat-packing facility.

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7. Link to origami animations.

8. Fabrication crew carrying the top dome. © Ariana Zilliacus.

9. Installing interior T-slot frame. © Karl-Johan Sørensen, Sebastian Aristotelis, SAGA Space Architects.

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Structural ring

The origami shell was unable to support its own weight in an Earth-gravity environment, necessitating the design of a structural frame to suspend it. Through an examination of the origami angles throughout the folding process, it was found that the horizontal cross-sectional lines remained in-plane during folding. This property allowed us to incorporate an aluminium ring mechanism without affecting the shell's folding capability. Upon full deployment, this ring could then be securely locked by bolting solid aluminium blocks at each hinge.

To ensure its rigidity at peak load cases, solid aluminium blocks were inserted at the connection points at the ends of each aluminium profile segment. This effectively transferred any moment forces arising from the complex load distribution of the origami shell to the ring, ensuring that these loads could be distributed into the ground through the feet and steel cables, minimising stress concentrations.

Legs

We opted for a design with three legs to ensure static determinacy and to enable the habitat to be levelled on uneven terrain. Each leg consists of two triangles, with pin connections at the habitat and moment connections in the jacks. The compression elements were constructed from 120x60mm square aluminium tubing, and the tension elements were from Ø9mm galvanised steel cables. The jacks can be elevated using a winch mechanism to accommodate uneven terrain, with a foot-to-foot variation of up to 1m.

Fabrication

LUNARK was built in-house at betaFACTORY by SAGA and a team of ten volunteers over two months during the summer of 2020. As this is a prototype habitat, fabrication closely paralleled the design process. We used a standard EXCITEC e2-1325 CNC router to cut all the carbon fibre and interior plywood panels. The same CNC router was adapted with an ethanol cooling system to mill all the solid aluminium blocks for the structural rings. Aluminium profiles were marked using the CNC router to ensure accurate dimensions and then cut with a metal band saw.

The only habitat components outsourced to a subcontractor were the heavy-duty Tungsten Inert Gas (TIG) welds needed to attach the cable fix-point brackets to the ring. Rubber seams were hand-cut using print-out templates and subsequently glued together. The entire habitat was assembled in less than a month, mainly by referring to the master model displayed on workshop screens. While our fabrication process may be considered low-tech in some aspects, it was appreciably facilitated and accelerated by the efficient transfer of information from the master model to our fabrication crew.

Transportation and site installation

The container with the habitat was shipped to northern Greenland on the final voyage of the season before the ocean froze. Karl-Johan Sørensen and Sebastian Aristotelis then journeyed to the remote, uninhabited location 40km northwest of Thule Airbase (now Pituffik Space Base). Here, the Danish navy dropped them off on the shore, where they received the container with the habitat. From then on, the two-person crew was isolated and solely responsible for unpacking and deploying the habitat in the extreme Arctic environment.

Unfolding the habitat

The entire structure was unfolded and installed using only battery-powered hand tools. After the container arrived on site, the habitat was manually dragged to the designated mission location on its wheeled platform. When deploying the habitat, a snowstorm struck, but the two-person crew persevered and successfully unfolded the origami shell in one workday.

The shell's unfolding process involved rotating three threaded rods, which acted as linear actuators, pushing the two structural rings apart. It was discovered, at the first folding test, that additional telescopic supports were necessary to stabilise the shell during deployment. Once fully unfolded, three aluminium legs were connected to the structural rings, and their jack-feet extended to raise and level the habitat. The Arctic environment significantly constrained the crew's ability to carry out manual labour, so easy assembly solutions were prioritised in the design. The interior assembly occurred in three main steps:

1. Installation of an aluminium T-slot frame.
2. Attachment of custom-made ArmaFlex insulation pillows to the shell's interior using Velcro.
3. Fixing the remaining panels to the frame, along with equipment and electronics.

An unforeseen deployment challenge was the physical toll of manually hammering the 15 1.5m ground anchors into the frozen ground. The crew could only manage a few anchors per day, as each anchor took approximately three exhausting hours to secure, resulting in a significant delay to the planned onset of the mission. For readers interested in the mission, more information can be found on the project website (*LUNARK*, 2020).

Transferability

The ecological collapse and climate crisis urgently call for us to diverge from the status quo of how we build. While LUNARK is a Lunar analogue habitat, it may be used as an example of how to build with limited resources on Earth in terms of material, time, energy, and knowledge. Although our climate crisis is already underway, we know little of what exactly to expect. What we do know is that our environments will become more extreme than what we are used to, and that many of the resources we take for granted will not be as readily available as they might be at present.

In the process of conceptualising and designing LUNARK, our greatest limitations were the size and weight of the final construction. These constraints shaped every part of the habitat and forced us to explore entirely new methods of design and construction. We believe that the extreme design brief of inhabiting outer space and the High Arctic, using limited resources, has resulted in a unique performative design that may be transferred to other situations that demand efficient logistics, fast construction, and robust structures that are semi-permanent and power-gathering. Examples of potential transferable use cases are emergency response shelters in disaster-stricken areas, mobile scientific research stations, and off-grid adaptable housing solutions in areas lacking infrastructure.

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Another consequence of said limitations was the footprint of the construction. In order to reduce our resource consumption, we must adjust the scale of our living standards. LUNARK is an example of a liveable building using minimal square meterage. Additionally, it is a successful example of a semi-permanent construction with minimal disruptive contact with the earth upon which it stands. Like a tent, it is removable by human beings working alone within one day, without leaving a trace that it was there, and does not require the laborious demolition or deconstruction that most buildings do. It is a less static and inflexible construction than we are used to, making it a well-suited example for iterative construction as needs and climates change at a rapid rate. At the same time, it is robust enough to exist without maintenance and controls in extreme weather, making it a candidate for long-term habitation without greatly affecting its immediate environment.

10. The habitat on site in the shipping container. © Karl-Johan Sørensen, Sebastian Aristotelis, SAGA Space Architects.

11. Rolling the habitat to its final location on site. © Karl-Johan Sørensen, Sebastian Aristotelis, SAGA Space Architects.

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12. Unfolding the habitat. © Karl-Johan Sørensen, Sebastian Aristotelis, SAGA Space Architects.

Finally, its power-gathering structure is an example of how one can easily integrate the harvesting of renewable energy into a building design. LUNARK used solar energy as both a primary and supplementary energy source, being entirely off-grid and only reliant on petroleum fuels during the sustained polar night.

Conclusion

LUNARK successfully demonstrates the benefits of an origami-based Moon habitat design by its ability to increase its liveable volume by 700% with minimal assembly and effort. Furthermore, in a world facing evolving resource challenges, LUNARK represents a novel alternative: a compact, lightweight, nomadic dwelling that can be easily collapsed and relocated as needed. Its potential utilisation lies between that of a tent and a shipping container, providing a flexible solution for various applications. The habitat successfully endured the challenging Arctic conditions for two months, verifying its off-grid functionality and ease of deployment. The execution and evaluation of the habitat prototype represent significant progress in the development of deployable, transformable structures and resource-efficient, lightweight, off-grid architecture.

Acknowledgements

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1

KNITNERVI
LIGHTNESS AND TAILORED MATERIALITY FOR FLEXIBLE CONCRETE CONSTRUCTION

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The significant impact of the construction sector on the environment demands a rethinking of design and construction practices towards more sustainable solutions. While reinforced concrete is the most commonly selected construction material due to its affordability and durability, its excessive use is a major contributor to global CO2 emissions and resource depletion (Lehne and Preston, 2018).

This paper describes the design, development, and construction of the *KnitNervi* prototype (Figs. 1, 2), which proposes an integrated flexible formwork system with bending-active falsework and 3D-knitted shuttering. The prototype was built for the Technoscape: The Architecture of Engineering exhibition, which ran from October 2022 to April 2023 at the MAXXI Museum in Rome, Italy (Casciato and Ciorra, 2023). The demonstrator was installed in the museum's entrance piazza and celebrated expressive and efficient structures, and interdisciplinary co-development in architecture, engineering, and construction. *KnitNervi* reimagines the compression-only dome structure of the Palazzetto dello Sport as a funnel-shaped (concrete) skeleton with a droplet-shaped central support.

The structure has a 9m outer diameter and a 3.5m inner diameter on plan, and stands at 3.3m tall. The structural skeleton is made up of a diagrid of compressive prismatic ribs connected to a boundary ring in tension. Due to the temporary nature of the installation, concrete was not cast into the diagrid rib structure. Rather, the focus of the demonstrator was on further developing a formwork system using 3D-knitted textiles, which is deployed using elastic bending to reduce the number of supports required and the amount of waste produced during construction, and to integrate controlled knitting detailing for both fabrication and construction. The absence of cast concrete on site allowed non-specialist visitors to the exhibition to see how structures are built up with a translucent textile, offering an 'x-ray through the structure' effect.

Alternative forming strategies

In current design and construction practices, the overuse of reinforced concrete largely derives from relying on it to provide structural performance through material strength, especially for large rectilinear spans. In contrast, structurally informed, compression-dominant, doubly curved, and rib-stiffened geometries can achieve the same performance with significant reduction in material use by

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obtaining their strength from their structure geometry rather than material strength (Block *et al.*, 2020). However, their articulated, non-standard geometry gives rise to construction challenges such as costly, materially wasteful moulds, and difficult to place and shape custom reinforcement. As such, conventional construction approaches can be among the primary obstacles for implementing materially efficient designs. As a result, innovative formwork solutions are needed.

To address these challenges, this paper presents a flexible formwork system developed as an alternative to traditional formwork solutions. Using a flexible membrane in formwork assembly offers new possibilities in structural, architectural, and manufacturing applications through simple means (West, 2016). The use of flexible formwork technologies relying on tensioned fabrics as moulds for concrete has been explored and successfully used since the late 1800s. An extensive overview of flexible formwork technologies is given by Hawkins *et al.* (2016). The system presented in this paper is an evolution of the KnitCrete flexible formwork system using 3D-knitted textiles (Popescu *et al.*, 2021). The approach represents an improvement over previous work through integrating the reinforcement and eliminating custom single-use external supports. This is achieved using a bending-active grid-shell as stay-in-place falsework in combination with a 3D-knitted shuttering to jointly create the formwork for a ribbed concrete structure.

Active bending allows slender elements to undergo elastic deformation and form 3D curved geometries without the need for additional intermediate supports (Lienhard, 2014). While flexible formworks based on tensile systems only allow for anticlastic geometries, using an active bending falsework allows for both anticlastic and synclastic geometries. Several explorations have been conducted on bending-active falseworks, including the use of textile shuttering and grid-shells (Tang and Pedreschi, 2015; Cuvilliers *et al.*, 2017). Combining bending-active systems with knitted textile membranes brings additional challenges in terms of simulating and modelling their hybrid interaction. These types of hybrid systems have been explored and developed in various demonstrators (Ramsgaard Thomsen *et al.*, 2018; Ramsgaard Thomsen *et al.*, 2015; Ahlquist *et al.*, 2013).

Integrated structure and formwork

The double-layered grid-shell structure is created by elastically bending slender straight rebars, eliminating the need for falsework. Its locked-in curved geometry provides sufficient stiffness while supporting the textile shuttering and ultimately being integrated into the concrete grid-shell as reinforcement. The structure of the bending-active grid-shell is determined through a form-finding process carried out with SOFiSTiK. The lengths and crossing positions of the splines serve as input for the third-order analysis, which equilibrates the system to achieve the form-found shape (Scheder-Bieschin *et al.*, 2022).

1. KnitNervi: Inner view of finished formwork system demonstrator. © Mariana Popescu.

2. Finished KnitNervi demonstrator at the MAXXI Museum in Rome. © Minu Lee.

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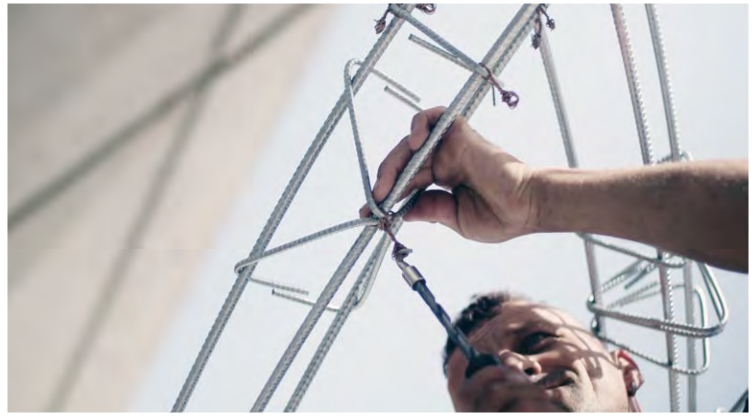

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3. Birds-eye view of the bending-active grid-shell during assembly. © Serban Bodea.

4. Assembly of grid-shell stirrups during construction of KnitNervi's bending-active grid-shell. © Thom-de-Bie.

5. Bending-active rebar grid-shell of the KnitNervi demonstrator. © Thom-de-Bie.

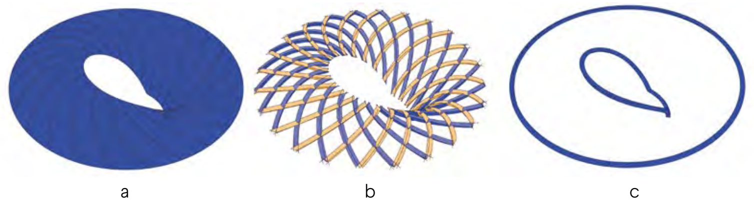
6. Measurement of bending-active grid-shell after assembly. © Thom-de-Bie.

The shell's diagrid structure is made up of triangular rebar cages (referred to as ribs) radially positioned in two opposing directions. The cross-section of these ribs consists of three splines laid out as a pair on top and a single spline at the bottom (Fig. 8a). To ensure sufficient stiffness and shape control, the two layers are connected with stirrups. Inclined, triangulating stirrups are used as shear-connectors between the top and bottom splines, while additional orthogonal stirrups maintain a consistent spacing between the longitudinal rebar splines. Together with the longitudinal splines, the stirrups create the rebar cage that remains in place as reinforcement for the concrete ribs. Akin to standard rebar spacers in construction, a simple custom 3D-printed spacer is fitted onto the rebar cage (Fig. 8a) to help tension the knitted textile shuttering into shape at the desired distance between shuttering and reinforcement. In a final tensioned state, the textile is coated with an eco-friendly clear resin that provides sufficient stiffness for concrete to be cast into the ribs without significant deformation of the formwork.

Production streamlining

A fundamental component of designing and fabricating such systems is an integrative design-to-fabrication workflow. By developing and using open and versatile computational framework COMPAS (Van Mele *et al.*, 2022), fabrication constraints are considered both in the form-finding and further engineering of the bending-active falsework's geometry (Scheder-Bieschin *et al.*, 2023) and the design and fabrication of the 3D-knitted shuttering.

The construction process of *KnitNervi* can be divided globally into two parts: 1) build-up of the bending-active grid-shell forming the rebar cage, and 2) build-up and assembly of the knitted shuttering. Each of these parts in turn consisted of two phases – a prefabrication and an in-situ assembly phase. In both cases, the prefabrication phase was geared towards creating a compact, lightweight, and easy-to-transport kit-of-parts to swiftly assemble on site.



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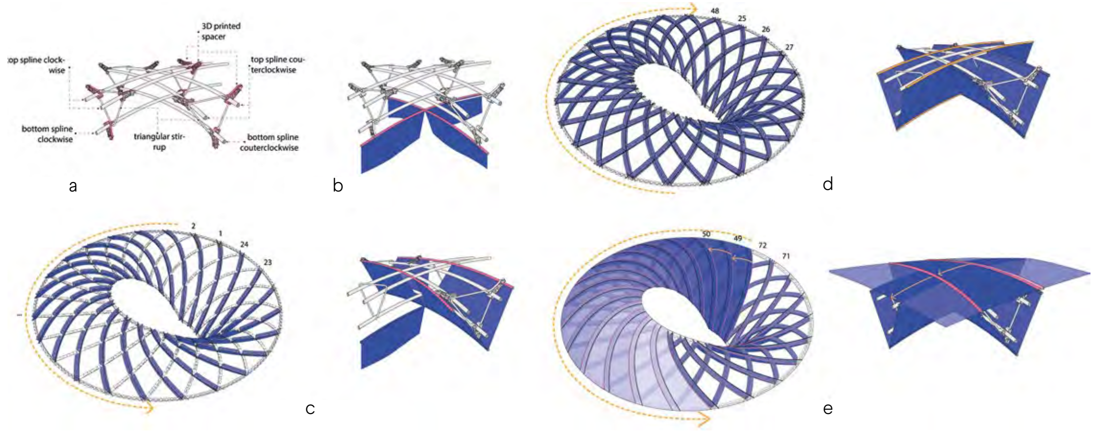

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Grid-shell falsework

The structure's main skeleton consists of two prefabricated boundary edge-rings, connected by bending-active grid-shell ribs. All fabrication data for the structure was derived from the computational model (Scheder-Bieschin *et al.*, 2022). The rebars, triangular stirrups, and edge-rings were prefabricated as a kit-of-parts. While the rebar splines were cut to size and stirrups were bent, the inner and outer edge-rings were prefabricated in two and six segments, respectively, by guiding splines through jig plates to maintain the desired shape. Each segment was then welded together using spline connectors.

To assemble the shell on site, scaffolding props were installed to support the grid-shell's inner and outer edge-ring segments. Telescopic props were used to adjust their height. The grid-shell ribs were then installed by sequentially connecting rebar splines to both edge rings (Fig. 3). This process began by attaching the top two splines of the triangular rib section in both directions and connecting them at marked crossings using rebar ties (Fig. 4).

While the stirrups were left hanging from the top splines in their respective sections, the lower spline was inserted through and connected to the edge-rings. Similar to the top layer, the bottom splines were connected at the marked crossings using rebar ties. Once all the elements were in place, the stirrups were moved into position along the splines and tied using rebar ties to ensure a consistent spacing and lock the grid-shell into shape (Fig. 5).

A total station was used to accurately align the structure according to the designed geometry. Measurements were taken at different stages of the assembly, including aligning the position of the edge-rings, monitoring the shape development of the grid-shell towards the desired form, and assessing the precision of the completed structure (Scheder-Bieschin *et al.*, 2023) (Fig. 6). These measurements also provided input for the fabrication pipeline of the knitted textile shuttering.

Knitted shuttering

Measurement data collected from the assembled grid-shell falsework was used to adjust and fine-tune the fabrication of knitted textile components. The ready-to-go streamlined production pipeline, coupled with on-site measured data, enabled a just-in-time delivery approach, ensuring that each component was manufactured precisely to fit its intended location in the structure.

7. Segmentation for production of the textile shuttering: a) 24 segments for the top surface spanning between two ribs, b) 24 rib segments in clockwise direction (yellow) and 24 rib segments in counterclockwise direction (blue), and c) edge-ring segments.

8. Sequence of attaching textile shuttering to the structure: a) attaching 3D printed spacers onto the rebar splines, b) attaching rib segments in both directions to the bottom spline, c) attaching rib segments in counterclockwise direction, d) attaching rib segments in clockwise direction, and e) attaching top surface.

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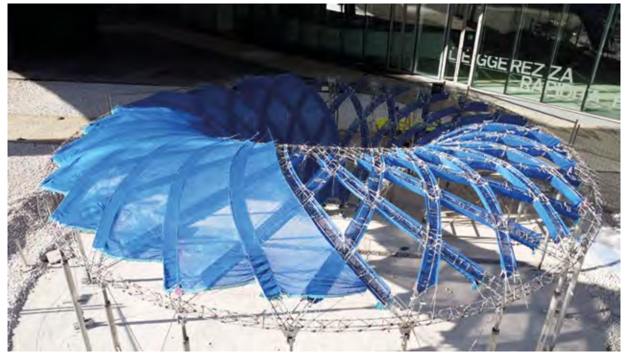

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9. Textile rib segments attached and hanging from the bottom splines of the grid-shell. © Mariana Popescu.

10. Assembly of 3D-knitted textile on bending-active grid-shell. © Achilleas Xydis.

11. Birds-eye view of knitted textile during assembly. © Mariana Popescu.

The shuttering's 3D surface was defined using curves representing the correct offset from the primary grid-shell structure. This included a top-layer surface that covered the entire area of the demonstrator, including a membrane between the diagrid members, and bottom surfaces for the triangular ribs in both directions.

For production purposes, the geometry was divided into 24 parts along the radial direction of the diagrid ribs in a counterclockwise direction. Each segment corresponded to the distance between two adjacent ribs. The entire demonstrator was made up of a total of 74 knitted parts: 24 parts for the top surface (Fig. 7a), 24 parts for the clockwise direction of rib segments (yellow in Fig. 7b), 24 parts for the counterclockwise direction of the rib segments (blue in Fig. 7b), and two parts for the edge-ring segments (Fig. 7c).

Aside from addressing fabrication size limitations, this segmentation also facilitated on-site handling and allowed for construction with a minimal number of workers. Additionally, it reduced computational intensity for generating the fabrication files and contributed to a better-controlled workflow. The textile design and production workflows are described in more detail in the following section.

Once produced, the textile parts were ready to be installed. First, thin rods were passed through channels in the textile while still on the ground, and ropes were placed in channels corresponding to the rib intersections. To tension the textile shuttering onto the grid-shell, 3D-printed spacers were fitted onto the falsework structure along all splines (Fig. 8a). These spacers were designed to easily clip onto the rebars with 'feet' that locked them into the right angle when inserted next to the distancing stirrups. Each spacer had three grippers into which the guide bars of the textile parts could be snapped. This allowed adjacent textile parts to fit perfectly next to each other without the need for sewing. This strategy enabled the structure to be disassembled into the constituent kit-of-parts without the need for cutting.

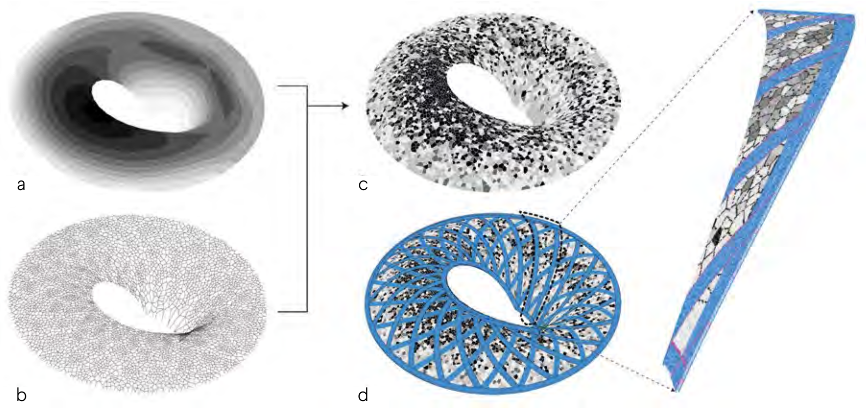
Attaching the textile shuttering to the structure was done in a specific sequence. First, the rib segments in the counterclockwise direction were attached to the bottom spline, leaving the sides hanging. Then, the rib segments in the clockwise direction were attached to the bottom splines (Figs. 8b, 9). The sides of the rib segments were then raised and attached to the structure using rods passed through channels in the textile (Fig. 8c). The same procedure was applied to raise the sides of the counterclockwise rib segments (Fig. 8d). With all sides of the rib segments raised, the node crossings were adjusted into position and tied with ropes previously inserted in channels at the intersection edges of the textile. After attaching and tying all the ribs, the top surfaces were placed into position in a radial sequence (Figs. 8e, 10, 11). Finally, the edge-ring rib segments were attached in the same way as the diagrid rib segments.

Controlled material properties

The textile's texture, density, and overall stitch-level architecture were designed with a hierarchy of functions. The rib sections, which would serve as formwork for casting concrete, have a denser texture, while the interstitial surfaces not used for casting were designed with a pattern of varying local densities. The distinction between porous and dense regions on the knitted surface is based on a conceptual definition of light and dark zones. The design intent was to have denser, more massive, and less transparent areas close to the ground and the periphery, while the areas close to the centre of the surface were designed to be lighter and porous. These zones were defined in Grasshopper3D using custom line and point magnetic fields that represented the desired level of transparency in each region (Fig. 12a).

Once the light/dark zones were established, the shuttering surface was divided into polygonal regions of various sizes. The regions labelled as 'dark' were subdivided into smaller regions compared with the 'light' zones (Fig. 12b). Each polygonal region was assigned a porosity value between 20% and 80%, which was represented in the model by the lightness of the grey colour assigned to each region (Fig. 12c). A darker grey indicated a higher porosity of the corresponding knitted surface.

The knitting patterns for each of the 74 parts were generated using the compas_knit package, as described in Popescu *et al.* (2017) and Popescu (2019). The patterns were colour-coded to mark functional features, such as channels, as well as regions of different porosity (Fig. 12d). The patterns were exported as BMP-format images (Fig. 13a) and post-processed using a custom Python script before being imported into the proprietary machine software. The post-processing aimed to transition from a pixel image where colour zones represent different porosity areas to a pixel image where each colour represents a distinct operation for the machine. This was done in two post-processing steps. Each pixel within the generated patterns represented a 4-loop-by-4-loop region on the machine. As such, the first step was to refine the pixels in the image to represent each needle position on the machine instead of a 4 x 4 region (Fig. 13b). In the



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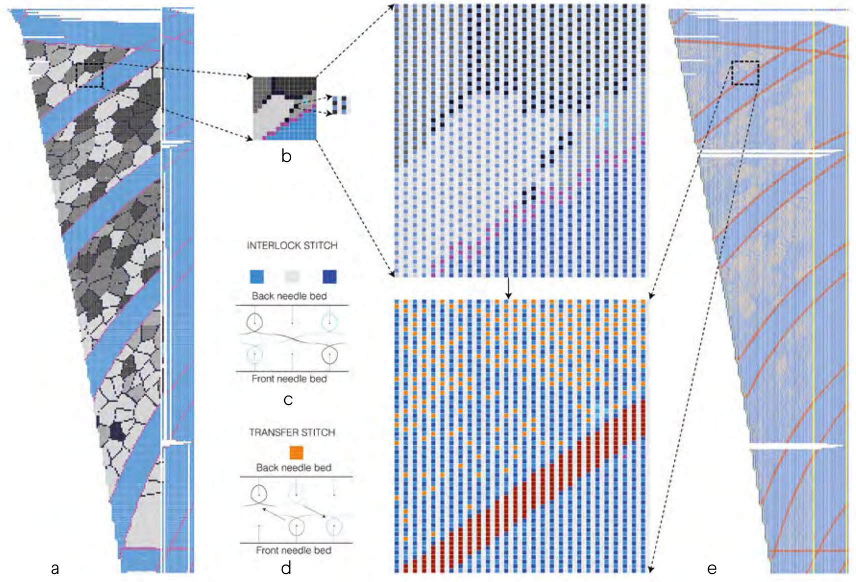

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12. Density regions and 3D-generated knitting patterns: a) fields representing desired transparency levels, b) polygonal regions for defining porosity values based on regions, c) porosity regions, and d) generated knitting patterns in 3D.

13. 2D knitting patterns and their refinement: a) 2D knitting pattern exported as BMP, b) first refinement step where each pixel is further represented as a 4x4-pixel pattern representing machine operations, c) interlock stitch operations, d) transfer stitch operation, and e) final post-processed image to be imported into machine software.

14. Detailed inner view of textile of finished KnitNervi demonstrator. © Mariana Popescu.

second post-processing step, transfer stitches (Fig. 13d) were added to populate large interlock stitch (Fig. 13c) regions based on the assigned porosity value. These transfer stitches form a small hole within the produced textile, thus creating variations in the local density of the pattern.

The post-processed BMP image (Fig. 13e) was then imported into the CNC knitting machine's software, where each colour was assigned a symbol from a custom-made library. Machine instructions were generated by translating each symbol into a distinct machine operation and combination of settings. The instruction files were used to fabricate the parts on a Steiger Vega T 3.130 CNC weft-knitting machine.

Discussion and outlook

The system described in this paper presents a computational workflow for the design and fabrication of flexible formwork systems. Such systems have the potential to address the challenges of forming and reinforcing complex structural geometry, as showcased on the ribbed shell formwork of the *KnitNervi* demonstrator (Fig. 15). The proposed structure combines design, structural engineering, and fabrication, integrating reinforcement and knitted shuttering into a single stay-in-place formwork. It eliminates the need for expensive custom moulds and pre-bent rebar cages. Additionally, the system is lightweight, self-contained, and self-supporting. It can be flat-packed for transport and easily deployed using a kit-of-parts approach, without the need for cranes or other heavy equipment. The construction process for both the rebar skeleton and knitted shuttering followed standard strategies and used common construction site tools. It involved a small team of skilled workers and was completed in two two-week sessions. However, working with such systems requires precision and diligence in construction, as well as a delicate touch and a rethink of building site accessibility. The sequencing of the build-up was crucial, making the process more vulnerable to mistakes. In this context, construction crews for such structures need to have an affinity for meticulous work and patience.

In light of the choice not to cast concrete into the structure, the demonstrator was unable to provide a full validation of the construction system for casting. In spite of this limitation, preliminary tests were conducted to assess the system's ability to withstand

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hydrostatic pressure during casting. Triangular-section beams, measuring 1.5m in height, were successfully cast vertically in one go, displaying zero or minimal deformation. In addition, a node section was cast and showcased in the exhibition. These tests demonstrated the feasibility of the approach for casting purposes; however, further investigation is required to determine the casting sequencing for the entire geometry.

With the ultimate goal of casting the structure, the design and assembly methods of the demonstrator were developed not only to be easy to assemble but also to allow disassembly into its constituent parts such that it could be rebuilt in a permanent location. This approach reflects on future-proof strategies with modularity and reuse in mind. By creating a shuttering that can be easily disassembled, there is potential to separate the stay-in-place knitted shuttering part of the formwork from the structure once it is cast, and potentially reuse it in the future.

Efficient computational pipelines for design have enabled the effortless extraction of fabrication data. This makes it possible to produce a kit-of-parts and split the construction of the grid-shell and knitted shuttering. This split provides time for waiting for a measurement of the as-built geometry, which is then used as input for fabricating the textile. The textile is measured and produced to fit accordingly.

Overall, by breaking away from standardisation paradigms, this demonstrator highlights the importance of sustainable construction practices and enables the building of expressive and efficient concrete structures. By using innovative design and manufacturing techniques, and addressing the challenges of materialisation, this flexible formwork approach could eventually help reduce the environmental impact of the construction industry.

15. Birds-eye view of finished KnitNervi demonstrator. © Mariana Popescu.

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TU Delft: Mariana Popescu, Nikoletta Christidi

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Project and site construction coordination
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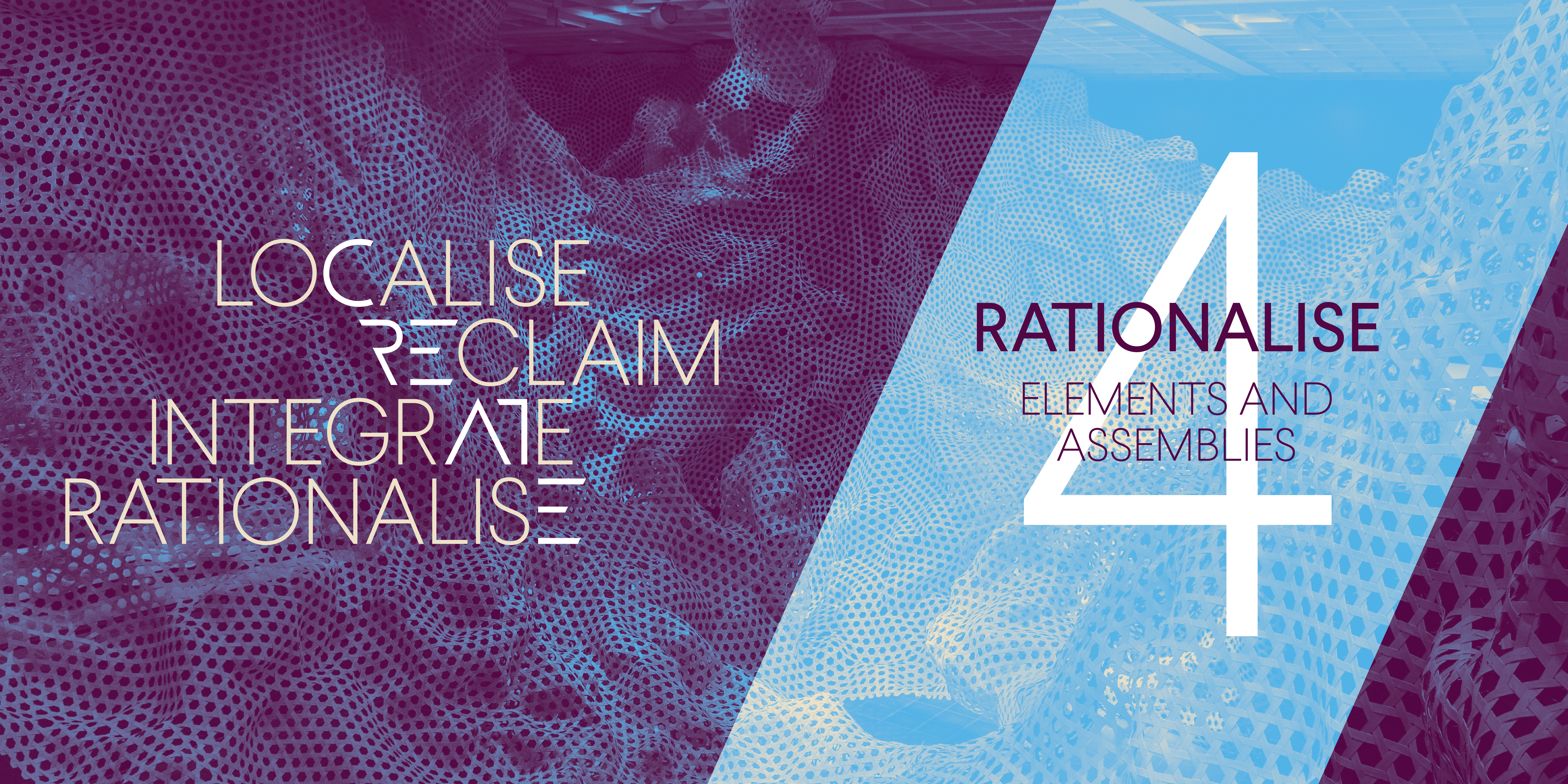


LOCALISE
RECLAIM
INTEGRATE
RATIONALISE

4 RATIONALISE

ELEMENTS AND ASSEMBLIES

1

WISDOME STOCKHOLM
FLAT-PACKED LVL-GRID-SHELL

FABIAN SCHEURER / SYLVAIN USAI / MORITZ NIEBLER
DESIGN-TO-PRODUCTION, ZÜRICH
JOHAN OSCARSON / JONAS ELDING
ELDING OSCARSON, STOCKHOLM

Summary

This case study presents an extension to the Tekniska Museet in Stockholm designed by Swedish architects Elding Oscarson. The 1200sqm building hosts a geodesic projection dome, covered by an innovative timber roof, both engineered and digitally prefabricated in Switzerland.

The column-free interior is covered with an asymmetric timber grid-shell that consists of five layers of doubly curved beams in two directions. Each beam itself consists of five layers of laminated veneer lumber (LVL). In contrast to recent large-scale timber grid-shells, in this design only the lowermost beam layer is laminated into a precise doubly curved shape. The upper four layers comprise flexible LVL-lamellae that are bent on site. Following installation, they are secured into their intended form using wooden dowels.

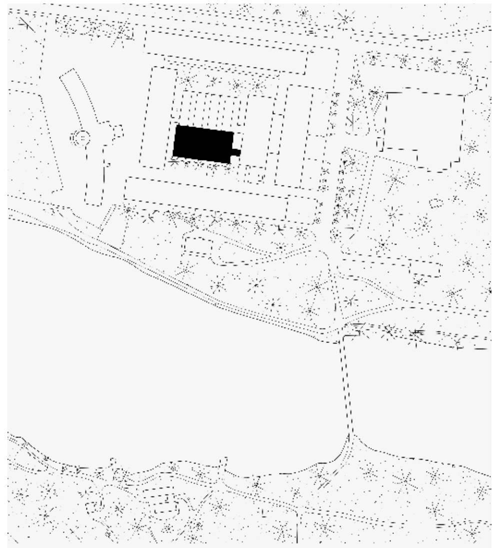
This innovative solution was primarily motivated by the predetermined choice of material, namely LVL, and constraints related to project schedules and budgets. The limitations made it impractical to pursue the traditional process of initially laminating and subsequently CNC-milling all beam segments. As an alternative, individual flat parts were CNC-cut from LVL boards, including all essential detailing. The wooden dowels were mass produced and everything was shipped flat-packed with preassembled timber columns and edge-panels from Switzerland to Sweden as a kit-of-parts.

Background

Wisdome are a series of advanced visualisation dome theatres built in Sweden to promote interest in science and technology. The last of five domes to be completed, *Wisdome Stockholm* is located at the National Museum of Science and Technology in Djurgården.

The project started as an invited architecture competition in 2018 and was made possible by donations and sponsorships from the local building and tech industries. The client's vision was to create a sustainable and smart wooden building. Stora Enso, one of the major forestry companies in the Nordic countries, teamed up with the client as primary partner and sponsor on the condition that the building should be constructed out of their engineered timber products, cross-laminated timber (CLT) and LVL.

1. Interior view of the timber grid-shell and the geodesic dome. © Mikael Olsson.



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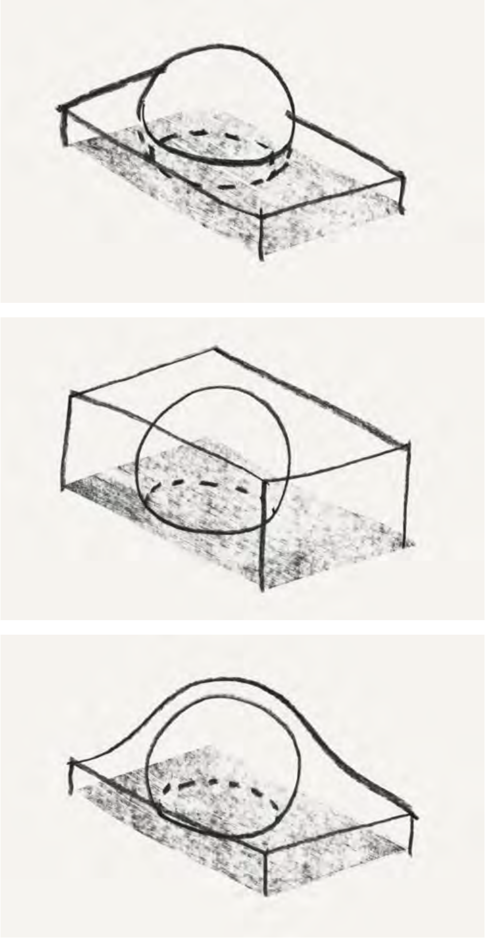

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The site was an internal parking area in the courtyard of the museum, surrounded by listed buildings from different eras and styles as part of a cluster of museums situated in the Royal National City Park, a historic and sensitive context with tight building restrictions. Apart from meeting the desire to create a contemporary attraction in Djurgården, the new addition provided the opportunity to address some problems in the existing premises, such as disorientation, poor circulation, and lack of daylight. The competition programme was condensed: the visualisation dome, a small café, and an open exhibition hall.

Design process

The geometry of the dome and the height of the building were limited by zoning regulations. Conventionally, the programme would generate a low volume with a protruding dome, but to create a strong interior space as well as a communicative exterior form, the unique dome was given a focal position under a free-form roof structure.

In a collaborative workshop with structural engineer Florian Kosche, the general design concept was established, and the roof assumed its final form. It mediates between the tall dome and the low façades of the one-storey building, spanning 26x48m across the dome. This generated an overwhelming interior space, while the oddly vaulted exterior communicates its unique function. By elevating the roof structure on columns, a seamless connection with the outdoor spaces was established, facilitating direct access from the museum to the courtyard and park. Strategically defined floor levels and connecting links allow the new building to connect

2. Site plan showing location in the museum courtyard, Royal National City Park, Djurgården. © Elding Oscarson, Stockholm.

3. Cross-section model of *Wisdome*, showing the projection dome. © Tekniska Museet, Anna Gerdén.

4. Conceptual sketches of design schemes. The chosen scheme both fully exposes the dome and keeps the building low to the adjacent buildings and courtyard. © Elding Oscarson, Stockholm.

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museum functions around the courtyard and, despite the considerable height of the dome, the added volume is respectful and sensitive to the existing vaulted hall and the other lower buildings defining the courtyard.

The idea of exploring the possibilities of a timber grid-shell emerged early during design studies. Frei Otto's 'Multihalle' was one of the central inspirational references, appreciated for the clever use of a basic material to create high architectural and spatial qualities. Bending thin strips of LVL boards, one of the materials made available by the sponsor, seemed to be an interesting take on the solid timber grid-shell. While this experimental approach carried inherent risks, it aligned closely with the overarching ambition of establishing a showcase for the Swedish timber industry. Preliminary structural analysis provided the necessary assurance to proceed, even though the project remained beset by many challenges.

As the design evolved, the client made the strategic decision to collaborate with a local contractor, bringing in their expertise in production and installation at an early stage. However, as they had little experience of advanced timber constructions, this led the project in a destructive direction, resulting in a compromised design. The structural concept from the competition was a four-layer grid of LVL strips, bent on site, combined with a dense shell of LVL boards on top. But in addition to uncertainties about production feasibility and installation time, there were rising doubts about on-site bending of the LVL, because cross-sections had to be increased to adhere to fire regulations. Other concepts were proposed as a back-up plan, but the time schedule and complications related to obtaining a reliable cost calculation put the project at risk.

Eventually, based on previous references and a convincing working method, a new partnership was formed with the Swiss timber contractor Blumer-Lehmann. In a design-build contract they were asked to present a plan for complete delivery of the timber structure, including production and installation as well as developing a structural concept matching the design scheme committed in the competition.

Engineering solution

Re-engineering began in the spring of 2021, after Blumer-Lehmann had gathered a team of timber specialists who had successfully collaborated on various grid-shell projects including the Swatch Headquarters by Shigeru Ban.

The key challenges in the *Wisdome* project were the constrained choice of material and the geometry of the shell. Contrary to Frei Otto's Multihalle, the shape of this roof was not form-found and optimised based on material properties and engineering principles. The design of Elding Oscarson results in high curvature and extreme torsion on one side of the roof, asking for high flexibility of the timber lamellae, while the opposite side of the roof has little curvature, thus attracting extensive bending stress and asking for stiff beams. Additionally, the shell is elevated on columns, which makes it difficult to cope with the horizontal thrust it creates. In combination, this allowed minimal margin for optimisation without undermining the original design intent.

5. Exterior view of the roof cladded in 85 000 hand-nailed pine shakes. © Mikael Olsson.

6. The interior space with the dome in CLT and the grid-shell roof in LVL. © Mikael Olsson.

To test the initial idea of bending LVL-lamellae on site, two large-scale demonstrators were built which delivered important results. Stacking lamellae and beams in four layers each created the intended design expression, and the necessary curvature and torsion could be achieved without too many problems. However, the concept of stabilising the shape solely through shear dowels between the lamellae proved unsuccessful, as the beams exhibited a recoil that significantly exceeded the stipulated requirements. To develop a concept that underwent successful testing on a 1:1 mockup in late 2021, three additional enhancements were introduced.

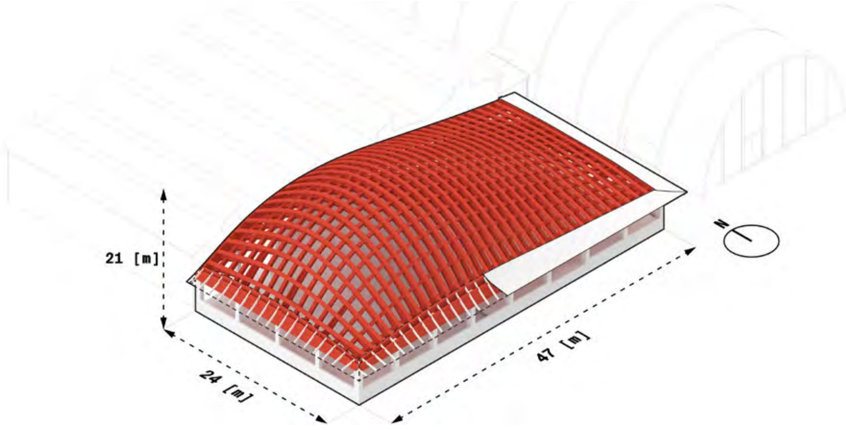
First, to ensure the requisite flexibility, the thickness of the LVL-lamellae was reduced to 31mm, and the number of lamellae per beam was increased from four to five. The roof shape and beam layout were slightly optimised within the design boundaries to further minimise local curvature and torsion.

Second, a fifth beam level was added to the initial concept. The now three beams along the short span and two beams of the long span are connected with wooden shear dowels to form a stiff shell system. It is connected to the prestressed columns via an edge beam and a bending-stiff joint, using massive shear panels between the upper two beams.

Finally, the beams on the lowest level are laminated off site into their final curved shape, to define a precise setting-out geometry for the roof. Only the upper four levels of beams are bent on site by stacking flat CNC-cut lamellae onto the shear- and cross-dowels.

This principle would be impossible to realise by means of traditional timber construction. But it becomes simple and obvious once the capabilities of digital planning and fabrication are fully understood and exploited:

- Precision: Transferring shear forces via massive timber dowels between layered but not laminated lamellae requires tight-fitting details in both beam directions – efficiently accomplished with the sub-millimetre tolerance of modern CNC-machines.
- Customisation: Rationalising the dowels to only a few mass-produced types requires thousands of individually cut connections on the doubly curved beams, which comes at no additional cost, since the lamellae are 5-axis CNC-machined anyway, with fabrication data generated directly from the digital model.



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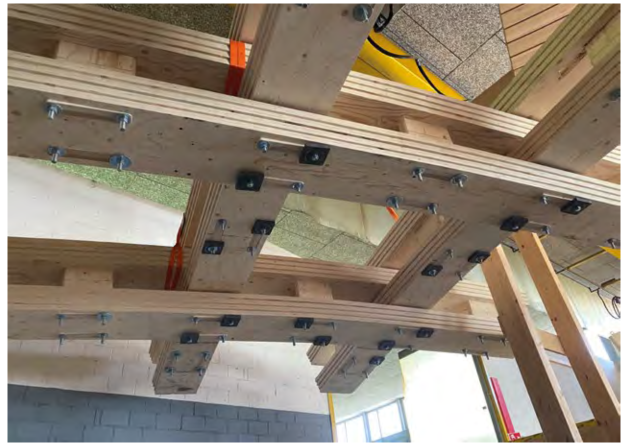
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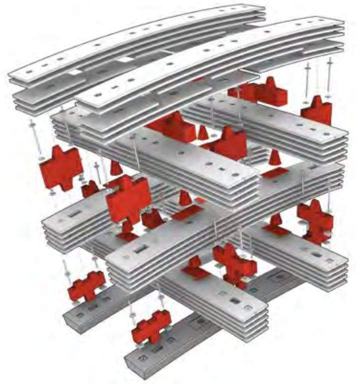
7. Dimensions of the *Wisdome* building in context. © Design-to-Production, Zürich.

8. 1:1 grid demonstrator: Stacking the lamellae and connecting the beams with shear dowels matched the design intention. © Design-to-Production, Zürich.

9. 1:1 mockup of the final concept to test tolerances and assembly strategies. © Design-to-Production, Zürich.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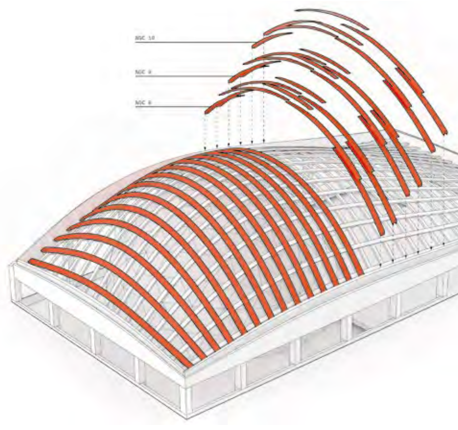
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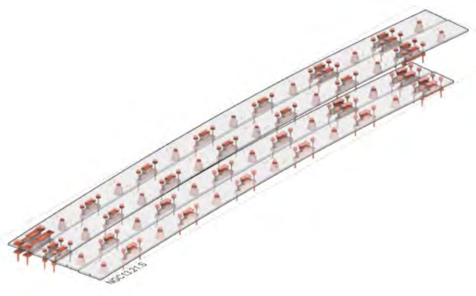
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10. Five layers of beams, each made from five layers of lamellae and connected by shear and cross-dowels. © Design-to-Production, Zürich.

11. Assembly sequence: Staggered joints allow assembly of long beams from shorter lamellae. © Design-to-Production, Zürich.

12. Production model: Lamellae and joint details were 'unrolled' and nested on flat boards for CNC-cutting. © Design-to-Production, Zürich.

- Simulation: Milling detailed lamellae from flat panels and fitting them together when bent to the curved roof requires modelling their curved state first and then precisely 'unrolling' them with their complex detailing, which can be automated by parametric 3D modelling that simulates elastic material behaviour.

The result is a flat-packed kit-of-parts, digitally fabricated from standard engineered timber material, easy to transport and assemble despite its impressive size – with all the complexities neatly resolved during the planning and production process.

A new digital workflow

Wisdome's digital workflow followed a scheme the team has been practising on complex free-form projects over the years and has gradually formalised since the Swatch project finished in 2019. Key to success is to pragmatically deal with three simple insights:

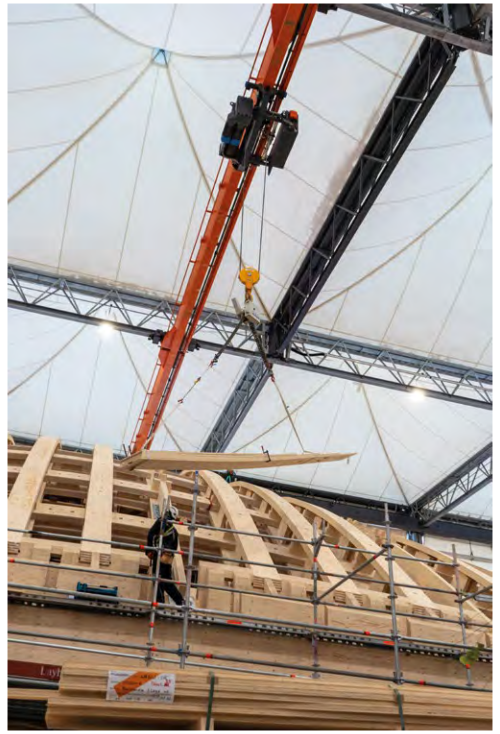
1. Digital project information grows over time – in this case almost two years. It eventually needs to converge towards ultra-precise and highly detailed production data, but it starts with rough design models and engineering sketches that need to be refined step by step and with defined milestones to handle changing responsibilities.
2. Free-form projects are complex due to a multitude of dependencies on all levels, arising not only from geometry but from the concept of prefabrication itself. They need to be identified and analysed early and in parallel, then untangled to avoid getting stuck in dead ends.
3. A team of specialists can resolve such a complex problem, but they will not just bring their own knowledge, but also their own (digital) tools and processes. Interfaces need to be agreed on, communication needs to be established, and information needs to be integrated into a seamless workflow.

The contradiction between a necessarily sequential process over time (1) and the integral development of solutions by addressing all topics in parallel (2) poses an insurmountable challenge for the classical 'waterfall' approach, which gradually 'drills deeper' into more topics over time. Therefore, a new, agile, and multi-scalar digital workflow was used for *Wisdome Stockholm*.

Digital parametric modelling

The *Wisdome* grid-shell contains thousands of individually shaped parts and geometrically complex joints. Digitally fabricating every drilling hole of this structure results in a true 'explosion' of information on the way from design to production data. Parametric modelling provides a solution to automate the generation of 'finer' detailed models from 'coarse' abstract models in a step-by-step approach:

- The initial 'reference model' only contained the design-surface, beam-axis grid, and placeholders for joints to analyse curvature and torsion of beams, identify extreme cases, and provide geometric information for structural modelling, to then optimise the geometry based on the results and fix the design.
- To generate the next iteration, the few components in the first model were then used as input for parametrically creating a 'coordination model' with some 3000 segmented lamellae, 3500 dowel volumes, and all other components, used to verify production



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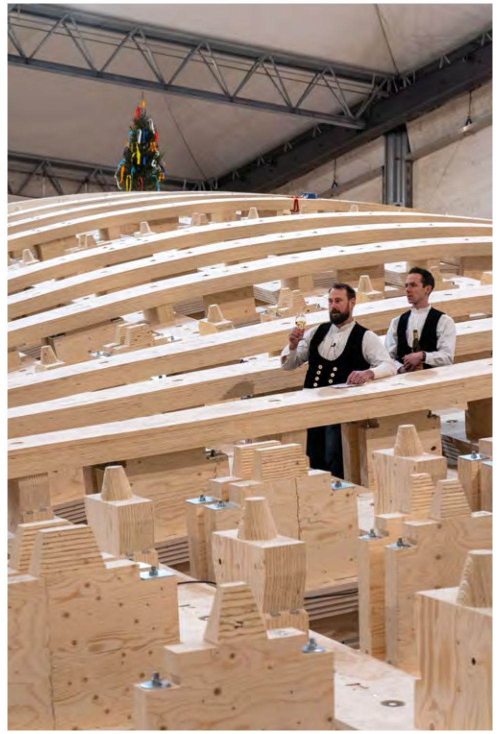

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and assembly concepts and order the raw material.

- Those undetailed components were then used in a third step to generate all the nuts, bolts, and cuts in the 'detail-model' – and eventually fabrication data.

Digital timber fabrication can achieve production tolerances of some tenths of a millimetre, which is necessary to meet engineering standards and create working connection details, such as tight-fitting shear joints. Parametrically generating fabrication data over multiple parametric steps will, however, only increase the level of detail (LoD), but not the level of accuracy (LoA) from model to model. Consequently, already the reference model needs to meet production accuracy, as any imperfection in the design surface will be faithfully replicated in the fabricated parts! Since there is relatively little information contained in this first model, paying close attention to accuracy is feasible – and pays off in a seamless parametric workflow downstream to production.

The beauty of parametric models lies not just in their efficiency but also in their flexibility. The first beam-axis grid might not yet be optimal, but it can already meet production accuracy. When it needs to change – for example, due to new findings by the engineers – all its joints can be updated parametrically. But this also means that the sequence of decisions defines the structure of the

13. Assembly: Lamellae were shipped and craned in stacked groups of five for easy handling. © Design-to-Production, Zürich.

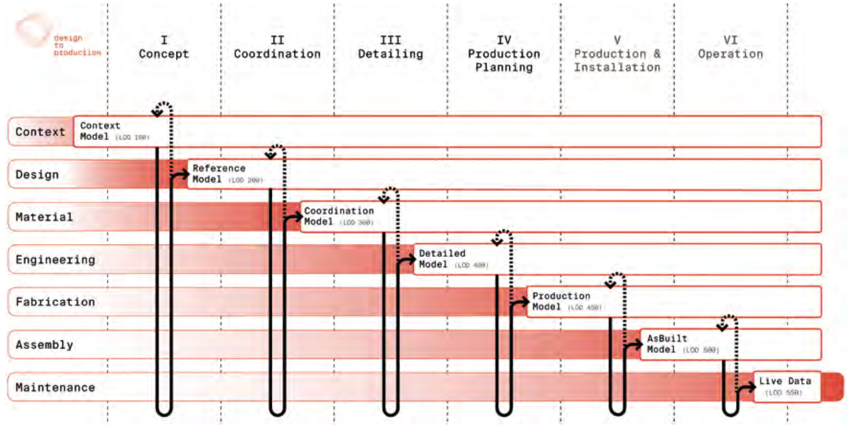
14. The entire construction site was protected by a tent during assembly. © Design-to-Production, Zürich.

15. Swiss carpenters during topping-out ceremony. © Design-to-Production, Zürich.

16: Agile digital process: Drilling deep through all topics from stage one, and step-by-step creation of a multi-scalar stack of differently detailed (but always precise) models over time. © Design-to-Production, Zürich.

17. From the catalogue of components, a matrix of connection details is created to systematically identify, develop, and document all necessary joint types. © Design-to-Production, Zürich.

18. Building components and joints are implemented as parametric types in an object-oriented way atop an existing component library. The *Wisdome* parametrics grew from stage to stage and in the end contained 28 joint and 49 component types. © Design-to-Production, Zürich.



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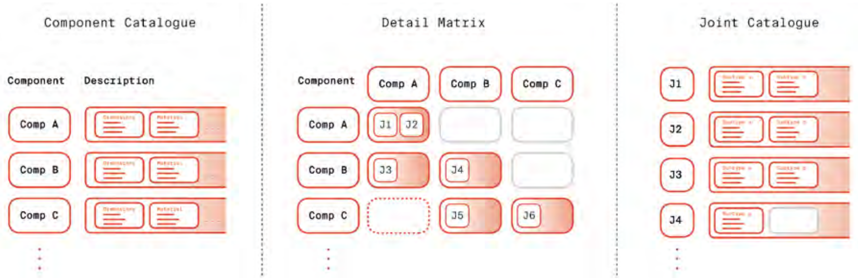

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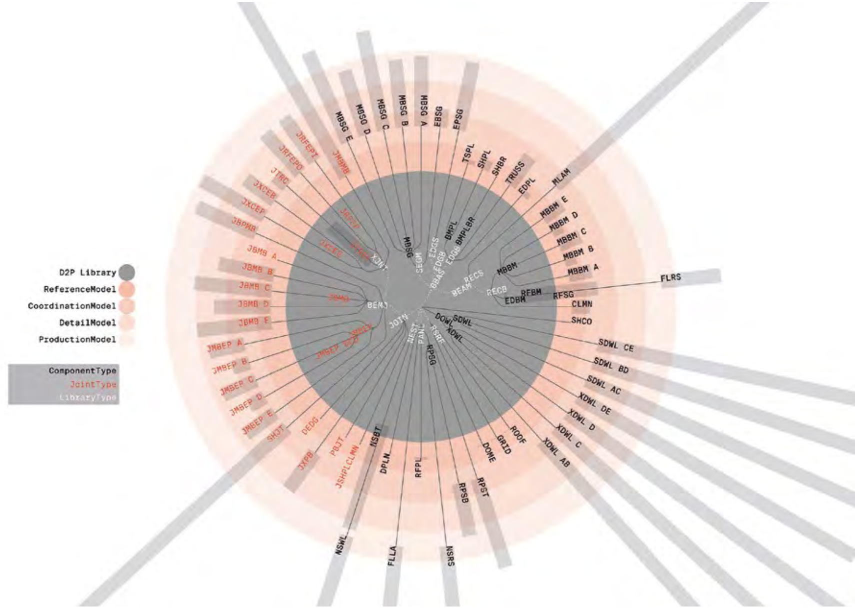

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model. The main task in parametric modelling is to distinguish between 'defining' and 'depending' and to identify and resolve circular dependencies, so that not 'everything is connected to everything' anymore.

Iteratively refining models does not work when the output model replaces the input model: once the necessary input is gone or outdated, the generation can no longer be repeated with changed parameters! Backtracking is impossible when only one increasingly detailed building model is used in the classical 'waterfall' process. Instead, building a growing 'multi-scalar' stack of models at different abstraction levels across all stages of the process makes it possible to 'dump and recreate' a finer level from the still existing and up-to-date coarse level at any time.

To implement parametric models, Design-to-Production uses Rhinoceros and Python scripts. Model components are defined in an object-oriented way, which makes it possible to build upon an already existing library of component types from previous projects – for example, to derive *Wisdome*-specific beam types from an already defined and tested generic type in the library.

Digital Design for Manufacture & Assembly

Whereas, in standard projects, fabrication and assembly are often regarded 'late topics', complex prefabricated projects like *Wisdome* require 'Design for Manufacture & Assembly' (DfMA) right from the start to ensure the feasibility and efficiency of the solution at all times. Starting a precise digital modelling process right at the concept stage allows it to inform the DfMA approach directly and results in an 'agile' design process with a working solution at every stage.

With close collaboration between engineering, fabrication, and modelling, the conceptual ideas for the *Wisdome* shell were repeatedly tested against the current state of the digital model – for example, to identify places where curvature or torsion of the beam geometry exceeded material capabilities, to find geometric worst cases where neighbouring joints would collide or fasteners could not be reached with tools during assembly, to check whether the lamellae could be nested into standard raw-material panels, etc.

The result is a steady optimisation of the concept and a growing catalogue of building parts to be implemented as parametric components. While traditional Building Information Modelling (BIM) is mainly concerned about parts but hardly ever about joints, the design-to-production process includes the systematic development of all connection details in parallel. A ‘detail-matrix’ identifies the necessary connection details between the defined components, and makes it possible to define and synchronise a ‘joint-catalogue’ for engineering and modelling and to extract essential inputs for developing the joint details from the model.

Digital process management

Solving *Wisdome* required an iterative approach, integrating all disciplines in close, parallel collaboration. Nevertheless, there were clearly defined project stages, separated by milestones that marked changes in responsibility. After the initial concept stage, the client was presented with a holistic engineering, production, and assembly concept, tested both on digital models and 1:1 mockup, and a cost estimate backed by a part-catalogue and model-based bill of quantities. After approval of this stage, the concept-model was refined to a coordination state where material orders could be approved (including a first unrolling and nesting of the still undetailed lamellae as early as four months before production). And finally, all joints were detailed, and fabrication data was issued for all the parts. To meet the tight schedule of the project, the later stages had to be overlapped: the part types were sorted by installation schedule and fabrication times and then pushed through the coordination, detailing, and fabrication stages in a steady two-week rhythm.

Also here, the digital workflow played an important role, since informed decisions could be made, based on the systematic catalogues and data from the model at any given time. But what was even more important was that all the interfaces had been clarified and tested in time: production data was issued in various data formats to all the fabricators involved, for raw materials, lamella-cutting, dowel fabrication, etc.

Conclusion

Topping-out of the timber structure took place in December 2022, and the opening of *Wisdome Stockholm* was scheduled a year later. This timber grid-shell unites an aesthetically striking yet demanding design with stringent boundary conditions, offering little room for manoeuvre when seeking a solution. Only the integral development of engineering, production, and assembly concepts in parallel with the digital processes allowed implementation of this unique experimental project within less than two years. It marks another successful application of a new process model, rooted deep in the collaborative exploration of similar projects by an experienced and dedicated team of specialists.

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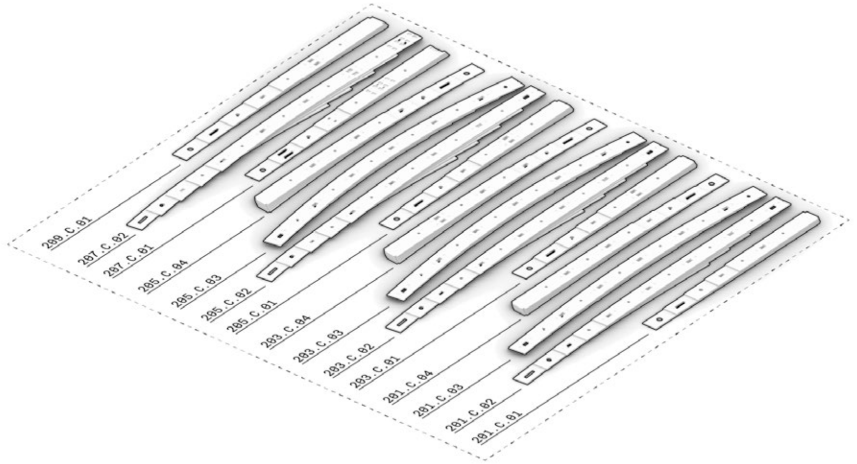

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19, 20 & 21. Keeping track of all parts through multiple stages – from 3D planning to unrolling and nesting for material order to production data, and finally logistics – is an inherent part of the digital process. © Design-to-Production, Zürich.

This building serves as a ‘proof-of-concept’ for the realisation of large-scale free-form structures constructed from flat panel materials bent on site. Compared with previous grid-shells like the Swatch project, this significantly cuts production time and cost by avoiding lamination and complex 5-axis machining on curved beams for four out of its five beam layers. Not only does this enable the use of a standard timber product like LVL-panels ‘off the shelf’, but it also widens the field of available fabricators that can support such processes with standard machinery. Future projects could therefore be fabricated locally, or become even larger and exploit distributed production. The trade-off is a slightly more complex installation process, handling bundles of flexible lamellae instead of laminated beam segments. But with proper DfMA, good process management, and logistics, those challenges proved to be more than manageable.

Wisdome Stockholm is already regarded as a pivotal achievement within the Scandinavian timber industry. It is expected to serve as a catalyst for the development of further innovative wooden projects, as well as to instil inspiration within local craftsmanship and engineering communities. In doing so, it closely aligns with Tekniska Museet’s mission to explore and elucidate the marvels of technology and science.

Project participants

Client: Tekniska Museet (National Museum of Science & Technology), Stockholm
Architect: Elding Oscarson, Stockholm
Civil engineering: DI Florian Kosche, Oslo
Main contractor: Oljibe, Stockholm
Timber engineering: Création Holz (Hermann Blumer), SJB Kempter-Fitze
Timber contractor: Blumer-Lehmann, Gossau
Material sponsor: Stora Enso
Fabricators: Blumer-Lehmann, Balteschwiler, Gebhard Müller
Digital process consulting + planning: Design-to-Production, Zürich

Acknowledgements

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TOR ALVA
A 3D CONCRETE PRINTED TOWER

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Advancements in 3D concrete printing

The enthusiasm of the participants captured in the historical video footage of the first 3D-printed wall more than 80 years ago anticipated an innovative trajectory for formwork-free concrete construction (Urschel, 1941). The act of autonomously fabricating a building using a mechanical rotary device to deposit concrete layer by layer, with minimal on-site human intervention, highlights a fascination with this progressive construction method.

Upon the reintroduction of 3D concrete printing (3DCP) with automated tools pioneered by Khoshnevis, a remarkable interest boosted research and industry developments (Khoshnevis, 2004; Wangler *et al.*, 2019). 3DCP is a digital fabrication process based on extruding fresh concrete filament deposited layer by layer to construct a digital design, with on-site printing and prefabrication as possible implementations (Wangler *et al.*, 2019). The former requires building an object vertically, in its final location, while the latter involves 3D printing several components that are subsequently assembled. In a broader context, this raised the question of how this novel fabrication method could change the building culture and what architectural language is best suited to 3DCP.

Today, however, some decades later, even though several 'first' 3D-printed homes are available, and a significant scale-up of the manufacturing process could be achieved, there is a certain disillusionment, and some observations give cause to reflect on past developments (Ma *et al.*, 2022). In fact, while one might find some rounded corners of vertical 3DCP walls, the architecture is typically far from demonstrating the structural potential of concrete, as even already shown more than a century ago in the simple Domino House concept by Le Corbusier or generic concrete-framed structures (Bischof *et al.*, 2022).

The evolution of 3DCP architecture to its present state can be attributed to technical constraints and the strategic selection between divergent development pathways. These decisions refer to opting for on-site 3D printing or prefabrication of components and the preference for low-resolution 3D printing with larger aggregates versus fine resolution with higher cement content. Additionally, determining the most suitable structural system, with options such as compression-only systems, stay-in-place formwork, or the integration of steel reinforcement, is crucial in shaping the architectural vision of 3DCP (Dell'Endice *et al.*, 2023; Anton *et al.*, 2021; Kloft *et al.*, 2020; Asprone *et al.*, 2018; Menna *et al.*, 2020).

Clearly, there is no one-solution-fits-all approach in 3DCP. For example, one can envision an on-site 3DCP system that utilises brick-sized extrusion filaments to produce monolithic masonry-like construction, admitting some compromise in precision and resolution.

The present research showcases a path towards the other end: a controlled high-resolution prefabrication scenario based on discrete assemblies of highly refined load-bearing components. In our interdisciplinary research (architectural design, building materials, and structural design), we refined these concepts through a fruitful collaboration with our client, the Origen Foundation (Origen Foundation, 2005). Our initial collaboration took shape through the creation of the Concrete Choreography installation, which comprised nine bespoke 3DCP columns utilised as stay-in-place formwork (Anton *et al.*, 2020). As the collaboration expanded in scope and vision, it led to the mutual evolution of the fabrication technique and its architectural application. The natural progression of a 3DCP stay-in-place formwork for columns is to directly 3D print load-bearing columns with integrated reinforcement. Moreover, segmentation, modular construction, assembly, and disassembly concepts are proposed for prefabricated 3DCP elements.

These innovative fabrication approaches will be exemplified and discussed within the framework of the Tor Alva project. Tor Alva is a 30m-tall tower located in the remote village of Mulegns, The Grisons, Switzerland, along the Julier mountain pass. This tower, designed for the Origen Foundation, serves as a temporary structure for art performances and installations, infusing vitality into a region experiencing a population decline. In addition to revitalising the area through cultural initiatives, the fabrication and construction of the tower actively involve local industrial partners, thus contributing valuable digital expertise through computational design and robotic fabrication. In this project, for the first time, a multi-floor building is built with load-bearing 3D-printed columns. Investigating principles of circularity and reuse, the tower will undergo a process of on-site assembly and five years of monitoring, followed by disassembly and eventual reassembly in a different location.

Architecture: Design for assembly and disassembly

The tower comprises 41 bespoke prefabricated concrete components interconnected using dry shear-keyed connections. Each component takes the form of a branching column with three distinct segments: column base (Fig. 1) and column capital (Fig. 3), which are precast in 3D-printed formwork, and branching columns that are

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entirely 3DCP (Fig. 2). Each segment is reinforced following the fabrication method: precast segments are fitted with a reinforcing bar cage, while the 3DCP columns have shear reinforcement placed between the layers during 3D printing (Fig. 4b). A load-bearing 3D-printed column is achieved by inserting longitudinal reinforcing bars into hollow channels that run through the entire component length (Fig. 4c). These channels are subsequently grouted to secure the bond between the longitudinal reinforcement and the printed concrete. Moreover, the components are post-tensioned with unbonded stainless steel rods, which are located in the hollow cores of the columns. The post-tensioning ensures the unity of the three segments as a single component, improves the force transfer through the concrete layers generated by the 3D-printing process, and avoids cracking of the 3D-printed material in the serviceability limit state. Each component interlocks with shear keys to its neighbouring top and bottom components and is connected at multiple points along its edges. The inclined branches of columns significantly improve the structural behaviour of the tower, as they transfer the lateral forces caused by wind or seismic actions via axial forces, which is structurally the most efficient solution. The column types range from having two to four branches (Fig. 3). In the design of the tower, each level has narrower columns than the preceding ones, ensuring a gradation of transparency along the vertical axis.

1. 3D concrete printing of the level 1 column of Tor Alva. © Nijat Mahamaliyev, Digital Building Technologies, ETH Zürich.

2. Detail of surface texture: material-driven ornamentation for one branching column.

3. The final design of Tor Alva has 41 components, assembled with dry connections.

4. Diagram of a bracing column component consisting of 1) precast base segment; 2) load-bearing 3DCP column: (a) outer layer for ornamented texture, (b) middle layer for shear reinforcing bar, and (c) inner layer for longitudinal reinforcement; and 3) precast capital segment.

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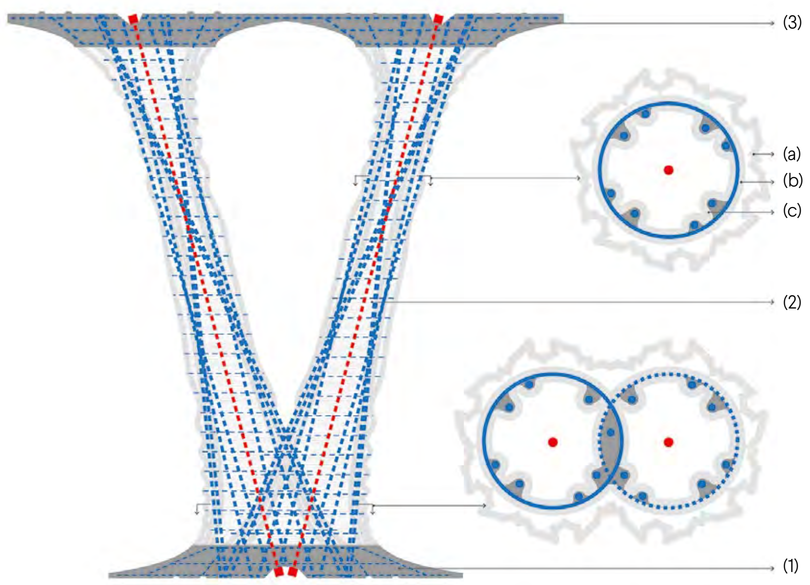

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The project relies on prefabrication arising from the need for precision of components and connection interfaces. This is essential for modular construction and disassembly, a key project feature, which enables faster production speed on site and reuse of the components.

When developing the tectonic system, we explored various detailing principles for 3DCP components. The design of this system took account of factors such as the scale of the production facility and transportation logistics. Achieving a concrete structure assembled with dry connections presents notable challenges for the 3DCP process, as it typically requires large tolerances. The approach proposed in this case draws inspiration from the match-casting technique commonly employed in precast segmental concrete bridges. A series of fabrication strategies for dry and permanent connections were tested in this context. To achieve sub-millimetre matching between dry-connected components, the parts are printed directly onto precast concrete components, milled timber formwork, or 3D-printed substrates (Fig. 5).

A comparable strategy was employed to produce the segmentation connections along the length of the 3DCP columns. This involved reprinting the last five layers of the previous segment as a substrate for the subsequent component. To facilitate easy removal, the 3DCP substrate was covered with a thin layer of plastic upon which the new segment was 3D printed (Fig. 6). The uninterrupted visual connection between the distinct 3DCP elements is achieved via material-driven ornamentation. The print path has purposefully integrated points along its length, resulting in an overhang of the concrete filament over the previous layer. As the material drips, it solidifies to form a non-planar feature (Fig. 6). In this approach, the connecting layer extends slightly onto the substrate, effectively concealing the gap between the elements. As a result, the assembly interface seamlessly aligns with the layered texture of the column, blending into the overall surface finish (Fig. 6).

Material: 3D-printing setup and material system

The 3D-printing process relies on a prefabrication setup, which involves dry-mixing material preparation and multi-component 3DCP (Fig. 7). The dry mix is stored in a silo with the supply flange connected to a M-Tec D10 continuous mixer. Material preparation in the mixer is triggered by a sensor that monitors the concrete level inside the pump. The pumping system includes three continuous cavity pumps: one PFT Swing L concrete pump and two ViscoTec ViscoPro C, one for accelerator and the other for thickener. The role of the extruder is to

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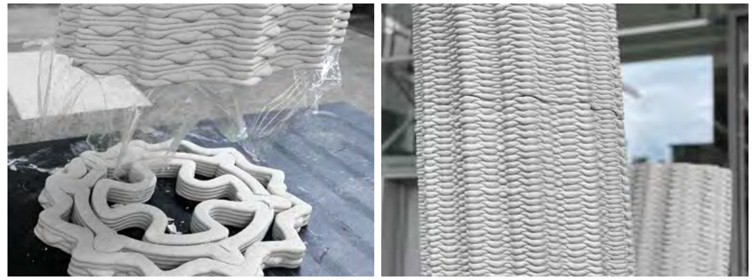

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blend the three components and dispense the filament along the print path. The extruder is mounted on the sixth axis of an ABB IRB 6700 industrial robot. The pumps and extruder are numerically controlled by the robot interface and monitored via pressure and temperature sensors. Throughout 3D printing, process data is recorded in an open-loop system with feedback, implemented through COMPAS FAB (Rust *et al.*, 2018) and COMPAS RRC (Fleischmann and Casas, 2020).

The dry mix is composed of a white Portland cement (CEM I 42.5R) at a proportion of $525kg/m^3$ combined with limestone (<125µm) and three grades of quartz sand (<0.1mm, 0.1-0.6mm, and 0.6-1.25mm). A superplasticiser and a viscosity modifier are also added in dry form, dosed to the cement content. The dry mix material is then directly mixed with water at a proportion that gives a water-to-cement ratio of 0.5. The accelerator is a slurry of white calcium aluminate cement and calcium sulphate anhydrite (1:2.1 ratio) at a water-to-powder ratio of 0.35. The thickener is based on a sodium metasilicate solution and a starch ether-based viscosity modifier. The accelerator and thickener are dosed at the printhead at standard ratios of 0.05 and 0.01 by mass of the concrete flow rate, respectively. The three components can be adjusted throughout the process depending on room conditions, with the accelerator dominating strength buildup behaviour and the thickener dominating initial yield stress, which governs the filament shape.

The system operates at a flow rate of 1.5 l/min with a print speed of 125mm/s, resulting in a filament 25mm wide and 8mm high (Fig. 8), where the latter dimension corresponds to the 8mm diameter inter-layer reinforcing bars. At present, the interlayer reinforcing bar is manually inserted during the 3D-printing process. The automation of this reinforcing bar insertion is currently in development and will not be addressed in this paper. Furthermore, the bases and the capitals are cast with conventional commercial concrete (C30/37), and the hollow channels are grouted with a commercial product.

One-to-one demonstrators served as tests for structural and fabrication concepts. The process started with stay-in-place formwork and gradually progressed towards load-bearing 3D-printed concrete columns.

The first demonstrator (Fig. 11) has ten segmental hollow-core columns connected between two continuous precast slabs through post-tensioning rods. Each column is prefabricated with a 3DCP outer shell one layer thick, within which a reinforcing bar cage and a hollow PVC tube are inserted before casting (Fig. 9). The PVC tube ensures enough space for the post-tensioning rods. The 3DCP formwork comprises two segments connected via a precast interface. The columns, cast with self-compacting concrete, have shear keys at the bottom. After curing, they are transported to the site horizontally. On site, they are connected to the precast slabs to test the tectonic and structural systems.

The creation of the demonstrator revealed several essential insights. One significant obstacle during the construction process, when using non-load-bearing, unreinforced 3DCP as a lost formwork, is for the formwork to withstand the hydrostatic pressures generated during concrete casting. Hydrostatic pressure is significantly higher in self-compacting concrete than in normal concrete. Initially, an attempt was made to mitigate the hydrostatic pressures generated by the fresh concrete by incorporating sand within an external formwork. Unfortunately, this approach did not prevent the failure of one of the columns. The final strategy consisted of pouring the concrete in stages, limiting each filling stage to a maximum height of 80cm. While this method effectively managed hydrostatic pressures, it significantly reduced the overall production speed.

From a structural point of view, the potential for optimisation of columns lies in using 3DCP as load-bearing elements (integration of reinforcement is necessary) and reducing the required post-tensioning by exploiting the maximum capacity of stainless steel (investigation of prestressing losses is required). This

5. Branching column with shear-keyed connections. © Ana Anton, Digital Building Technologies, ETH Zürich.

6. Assembly detail of a segmented 3DCP column: removing one segment from the substrate and assembling it to the adjacent component. © Ana Anton, Digital Building Technologies, ETH Zürich.

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7. Fabrication setup for the building-scale demonstrator. © Rami Masallam, Digital Building Technologies, ETH Zürich.

8. 3DCP of the branching column prototype. © Ana Anton, Digital Building Technologies, ETH Zürich.

aligns with the sustainability perspective, since using a high-performance material such as 3DCP as stay-in-place formwork is wasteful unless the 3D-printed material is activated to transfer loads. However, compared with lost formwork, utilising load-bearing 3D-printed columns requires structural testing to ensure a safe design. Furthermore, the design of the columns was found to be overly conservative, requiring too many vertical columns to achieve the desired architectural vision of an enclosed and protected space. The connection details between 3DCP segments, the grey precast concrete stripes located at one-third along the height of the 3DCP columns (Fig. 11), were refined to align with the space's aesthetic requirements (Fig. 3).

The findings from this demonstrator confirm the viability of the building sequence and structural approach. However, after the project's evaluation, innovative load-bearing 3D-printed columns, together with remarkable architectural, tectonic, and structural redesigns, will be introduced in the final tower project.

A more ambitious approach to 3DCP was embraced in the broader project development. This shift involved designing columns with geometries that could not be readily produced through conventional fabrication methods. Transitioning from vertical to branching columns ensured a more efficient and stiffer structural system, and hence a reduced number of columns and a smaller number of inner post-tensioning rods.

Moreover, part of the 3DCP material is now structurally activated following a three-layer approach: the outer layer creates the ornamented and visible texture of the column, the middle layer accommodates the shear reinforcement, and the inner layer creates hollow channels for inserting the vertical reinforcement (Fig. 4). This approach to reinforcement breaks down the traditional reinforcement cage into separate vertical and horizontal steel elements that are positioned in space concurrently with the 3DCP process (Anton *et al.*, 2022). Unlike entirely hollow columns, the trunk of the Y-shape preserves the logic of branching by intersecting the paths of the individual branches, thus ensuring the uninterrupted flow of forces within the structure. While the layer print path in the trunk area of the column becomes relatively complex, the shear reinforcement maintains a circular shape. It is placed at an offset height to avoid collisions with neighbouring branches.

Sustainability, impact, and vision for 3D concrete printing

Initially, 3DCP was introduced as a means to boost productivity and minimise material consumption in concrete construction. Intensive research on this fabrication method reveals unique opportunities and clear constraints. The transformation of 3DCP into a genuinely effective tool for reducing resources (considering workforce, formwork, and concrete) in construction demands a multi-disciplinary approach that fuses architecture, material, and structure into a comprehensive fabrication method.

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There are clear advantages to using 3DCP in construction, including creating customised structures, eliminating the need for formwork, and introducing automation. However, there are also many challenges associated with this fabrication method. These include issues related to 3D-printing speed, material formulation, aggregate size, cement content, reinforcing bar integration, accuracy, structural performance, and durability, among others. Selecting the appropriate options among the many possibilities enabled by 3DCP is a critical question towards paving the way for sustainable concrete construction.

The research behind the Tor Alva project moved away from the homogenisation of fabrication, as experienced in the industrial age, to a heterogeneous, rich architecture that celebrates diversity, individuality, and adaptivity to the local context.

3DCP enables a significant shift in the level of resolution achievable in both computational design and digital fabrication. The Tor Alva project serves as an example of how columns can be intricately designed with a resolution as fine as 8mm, matching the layer height of the 3DCP process. This layer height not only determines the material-driven ornamentation on the visible concrete surface but also influences factors such as the placement and diameter of shear reinforcement and the design of the assembly interface between 3DCP components. This fusion between structural system and ornament in 3DCP elements brings this technology closer to digital craftsmanship.

The exploration of reinforcement strategies for 3DCP highlighted several promising avenues for the future of concrete construction. Designing concrete reinforced elements starting from the reinforcement layout enables the creation of hollow structural elements with slender sections. Building on these advancements, our vision extends to developing digital composite materials in which both reinforcement and concrete are strategically placed for optimised lean shapes.

Beyond the focus on material efficiency, the architectural objective is to create designs that can actively engage with and contribute to the social and cultural aspects of society. Tor Alva demonstrates that 3DCP can help construction to move from volume to value by consequently building with thin-shell, hollow concrete elements. Moreover, the chosen structure, the tower typology, is a scalable system particularly suited for denser construction. In the Tor Alva project, these aspects are integrated through developing a novel formal language for 3DCP, integrating circular construction, assembly and disassembly strategies, and customisation. Through these initiatives, the project paves the way for an enhanced sustainable construction practice that is scalable and quickly disseminated throughout the building industry.

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9. Assembly of reinforcing bar cages and casting process for the demonstrator. © Ana Anton, Digital Building Technologies, ETH Zürich.

10. Assembly of the building-scale demonstrator. © Eleni Skevaki, Digital Building Technologies, ETH Zürich.

11. Building-scale demonstrator consisting of ten columns assembled with dry connections. © Michael Hansmeyer, Digital Building Technologies, ETH Zürich.

12. Assembly of a segmented branching column. © Ana Anton, Digital Building Technologies, ETH Zürich.

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WOOD FLOW
MATERIALITY, AGENCY, AND HYPER-LOCALITY

MARTIN SELF
XYLOTEK

Introduction

This paper presents two collaborative projects realised by Xylotek that develop novel approaches to forming complex timber structures. Both projects, the Osnaburgh Pavilions in Regents Place, London, and Westonbirt Community Shelter in Gloucestershire, use novel combinations of elastic bending and twisting, steam bending, and glue lamination to manipulate wood lamellae. They illustrate efficient approaches to utilising wood that maximise the synergy between the chosen species' characteristics and the desired architectural outcome. The paper considers both the technical issues involved in fabricating curved forms in wood with minimal industrial processes, and modes of design and making practice that enable inclusive engagement in that fabrication.

Both projects were delivered by Xylotek, a UK-based timber specialist design consultancy and construction company, who work on non-standard projects ranging from the small pavilion-scale projects discussed here, to large mass-timber buildings. The company's members have previous experience in grid-shell and geodesic-path structures. This includes projects at Hooke Park, Dorset, UK, realised with students of the Architectural Association, including a timber seasoning shelter formed of steam-bent locally sourced beech planks (Menges *et al.*, 2016). While at Carpenter Oak & Woodland, current Xylotek director Charley Brentnall was involved in oak grid-shells at the Earth Centre, Doncaster, and the Chiddingstone orangery roof, which demonstrated the potential for glazed timber grid-shells (Chilton *et al.*, 2016, p.54). The author, Brentnall, and a third partner, Oscar Emanuel, founded Xylotek in 2018, with an early project being with Foster + Partners, Expedition, and Bath University, which established the potential for glue-laminated bamboo grid-shell structures following geodesic paths (Sharma *et al.*, 2021).

Consisting of a set of open-lattice grid-shells for a public space, Osnaburgh Pavilions are a series of small-scale enclosures formed of geodesic glue-laminated oak laths. The second project, the Community Shelter at the Westonbirt National Arboretum, presents an alternative form of fabrication practice for realising complex architecture in a hyper-local context. It was designed and delivered in collaboration with mixed-ability community groups. Both projects share the principle of using timber ribbons following geodesic paths, meaning that initially straight planks could be used with little subtractive

1. Westonbirt Community Shelter. © Jim Stephenson.

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machining, with the benefits that material wastage is minimised and grain fibres are mostly left intact. Both projects required close digital and verbal feedback between architect, engineer, and workshop teams to find optimum geometries, processes, and material configurations. Throughout the projects, the choice of sources of wood – and later selection of individual pieces – was critical to ensure a close synergy between the wood's characteristics and the intended geometric forms. This synergy extends to the importance of human agency in processes of making, and its capacity to manipulate and handle wood components.

Osnaburgh Pavilions

Osnaburgh Pavilions are a set of three lattice structures, designed by architects Nex for British Land to provide landscape features in their Regent's Place office campus redevelopment in London. They consist of oak grid-shells detailed, fabricated, and installed by Xylotek, working with Format Engineers. Xylotek joined the project in RIBA Stage 3, and worked with Nex to develop a geometric and structural logic that suited the architectural intent, material behaviour, and installation constraints. The brief prompted a set of questions: how to create the free-form dome shapes with optimal material efficiency; how to use wood in a form that would be tactile and maximise its role as a natural landscape feature within a commercial urban context; how to maximise prefabrication to suit the tight space and time window for installation.

Precedents for the pavilions came from the history of timber grid-shells, which is well presented by Chilton and Tang (Chilton and Tang, 2016), who describe the evolution through early grid-shells such as the Mannheim Multihalle and the subsequent development of the deployable method of forming from flat lath grids, through recent alternative systems. The externally exposed deployable oak grid-shells by Grant Associates at the Earth Centre, Doncaster (1998) (Chilton and Tang, 2016, p45-46) were visited to assess their performance and weathering rates since their installation, giving confidence in our proposed use of oak. Another key reference was the set of interior grid-shells at Hermès Rive Gauche, Paris, by Rena Dumas Architecture Interior (Bollinger and Grohman, 2011), which was built from plywood lamellae, each CNC-cut to unique curves. The Osnaburgh Pavilions, however, are external, so the approach of using durable hardwood glulam was pursued, using initially straight finger-jointed oak ribbons following geodesic lines across the defining surface of the structures.

The benefits of using of geodesic curves in grid-shell structures have been described and realised by Natterer in the Polydôme at the École Polytechnique Fédérale de Lausanne (EPFL) campus (Natterer *et al.*, 2000), more generally by Weinand and Pirazzi (Weinand and Pirazzi, 2006), and exploited in recent projects such as the Steampunk Pavilion in Tallinn (Jahn *et al.*, 2022). As bending is limited to one direction, a rectangular section can be used – rather than the square section of traditional grid-shells. This means a cross-sectional area of material can be maintained for carrying axial loads at acceptable stresses, while the smaller minor-axis dimension allows for tighter radii of curvature to be created in that direction. This allows for more variant geometry to be formed than that in a deployable grid-shell, and suits glue lamination from thin ribbon lamellae.

2. Osnaburgh Pavilions, Regents Place, London. © Mike Audet.

3. Osnaburgh Pavilions, Regents Place, London. © Luke Hayes.

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4. Preparing oak lamellae for layup in the glue-lamination jig for the Osnaburgh Pavilions. © Martin Phelps.

5. Lamination clamping jigs for the Osnaburgh Pavilions. © Martin Phelps.

In the Osnaburgh Pavilions, the glue-laminated laths forming each pavilion are arranged in four layers, with alternate layers spiralling in opposite directions. An inclined surface-of-revolution was defined for each pavilion as the reference surface onto which the geodesic paths were mapped. Within each layer the laths share self-similar geodesic curves, meaning that all the laths in one layer could be formed on a single bending jig. Visual variation was created by adjusting the laths' lengths in a repeating pattern overlaid with some randomness. There are more than 400 laths, made of more than 10km of oak lamella strips. Each oak lath has a cross-section of 65 x 40mm and is made of five layers of 8mm oak lamellae.

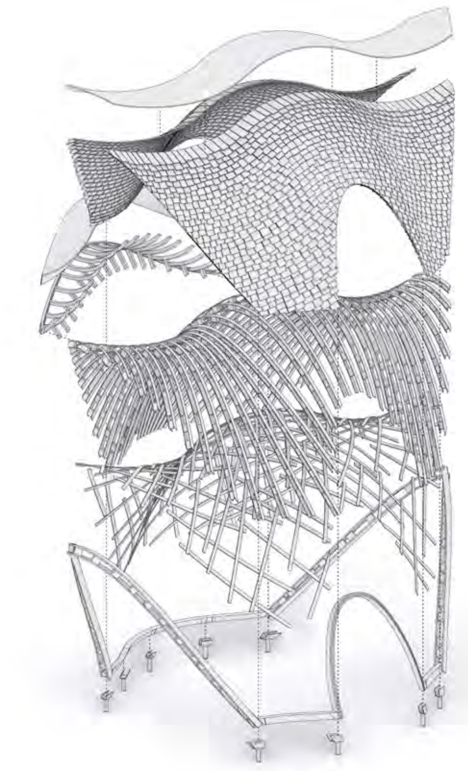
The grid was formed by connecting together pairs of laths at their crossing points with a single bolt through each lath's centreline. An oak spacer block was added for the conditions when laths were not on adjacent layers. The connections were distributed to ensure structural strength but also to use the wood's inherent flexibility to ensure that no single bolt connection was overloaded.

Format Engineers developed a novel technique for optimising this distribution of connections. Through iterative analysis and redistribution of the bolts, an arrangement was found in which the number of connecting points was minimised and no connection was overloaded. The algorithm worked counter intuitively by culling connections that were overloaded, rather than adding more connections in areas where forces were highest, thus avoiding a 'death spiral' situation in which increased density of connections simply attracted more force to that area. The algorithm worked iteratively to add and remove connections, while also ensuring a maximum length of unconnected lath was not exceeded to maintain buckling strength and general robustness in the structure. In this way, an optimised structure emerged that was working in sympathy with wood's natural flexibility.

Sourcing oak for the project was challenging. Wood that had been externally air dried for several years was sought, to give confidence that it had steadied at a moisture content that would be both stable in its exterior environment and consistently dry enough to allow it to be processed and glue-laminated. A suitable stock of well-dried European oak was found in northern France. These raw boards went through several stages to produce the lamellae used in the glue lamination. They were initially sawn to oversized planks, which were then finger-jointed into 10m lengths in a process that automatically cuts out knots and other flaws. These were then cut in half to create two lamellae at about 68x10mm in dimension. These were transported to Xylotek's workshop in Bristol ready for glue-up.

Since glue lamination needs to be done on freshly cut wood surfaces to ensure good penetration of the glue into the grain, it was necessary to have a production workflow that ensured that each lamella was planed down to its final dimension within 24 hours prior to gluing. A process was set up in the workshop to prepare the lamellae, stack them in groups, pre-apply the glue, then transfer the lamella sets to the laminating jigs. These consisted of doubly curved bending and clamping jigs formed of a 'waffle' of parallel CNC-cut plywood sheets into which the bent profile was cut. The jig was longer than any individual lath, which was defined as just part of the original self-similar geodesic ribbon. Thus, each of the 400 laths had a different length, which needed to be communicated to the workshop team. Digitally automated drawings defined the end cut position of each lath relative to the vertical plywood planes of the bending jig. The laths were glued up slightly over length, then marked up in the jig, and once off the jig were cut to exact length.

The bottom ends of each lath were cut square, and slots were cut for flitch plate connections to steel footings. Each lath meets the ground plane at a different compound angle, which was taken up in the geometry of the steel shoe elements. The shoes were welded to base plates, which were in turn fixed to a buried steel ring beam foundation. Segments of each pavilion were preassembled onto those baseplates in the workshop. These segments were defined to have a size suitable for road transport and to have their own structural integrity. On site, these segments were installed first and provided a framework onto which the remaining laths were overlaid, tying the whole structure together and creating the full 3D lattice of curved oak. This approach meant that minimal temporary supports were needed on site, keeping site time, and wasted material, to a minimum.



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6. Exploded diagram of the structural and envelope layers of the Westonbirt Community Shelter.

Westonbirt Community Shelter

The Community Shelter at Westonbirt Arboretum was commissioned by Forestry England to create space for educational workshops, within the woodland at the UK's national tree collection. Xylotek and Invisible Studio won the competition to design and deliver the project through close engagement with community groups who would ultimately contribute to building the shelter. The client's brief was for an inclusive ethos throughout the project, and therefore required the team to formulate a project that could be developed through design prototyping and construction workshops with people of mixed abilities. The construction process therefore needed to be accessible without requiring advanced skills. Group participants included adult volunteers, and children and young adults of varying special needs and capabilities. This ambition for 'spatial agency' (Awan *et al.*, 2011) to be available to all participants was the prime driver for the project.

A key part of the brief was to use wood directly sourced from the arboretum. The project is the latest of a series of buildings at the Westonbirt commissioned by Forestry England, each of which have tested radical approaches to using timber from the woodland. One example, the Wolfson Tree Management Centre (TRADA case study), has a roof truss formed of massive hewn Corsican pine members up to 20m long. Early visits to the arboretum identified mature oak trees that had outgrown their locations and needed to be felled. The standing trees were inspected, and their available timber volume dimensions and likely quality were assessed. In the following months these trees were felled, extracted from the woodland, and initial oversized boards were cut using an on-site sawmill.

The client was adamant that the shelter should have a compelling and unique architectural form that would encourage community group activities and ensure that all who participated would feel that they were in a special space. The shelter needed to combine a sense of enclosure, enable groups to gather, and provide eye-level visual connection across the surrounding clearing to help supervision of participants both inside and outside the pavilion. The shelter's form originated in hands-on community workshops in which 1:5-scale prototype structures were built using material available at the site. The idea emerged of a barrel-shell, symmetrical on its long axis and opening up at both ends. It was created ad hoc from thin oak ribbons laid up progressively to form the shell. The first step was to make lateral arches to form the initial barrel shape, and then cross pieces were progressively added to increase triangulation of the structure and generate the cantilever end of the roof.

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7. Fitting of the discrete bracing elements of the Westonbirt Community Shelter. © Martin Phelps.

Variations on the approach were created in parallel in one afternoon session, and the merits of each discussed. The preferred structure's geometry was then captured through photogrammetry and used as the starting point for digital design development of the pavilion. A proposed surface form was modelled based on that 3D scan and initial structural configurations tested by Xylotek and Invisible Studio.

Reflecting the approach of the 1:5 prototyping, a rationalised approach of transverse arches with 'flocks' of ad-hoc bracing was developed. Once defined digitally, a second community workshop was held, this time focusing on model-making at a smaller scale with the aim of testing the methods of forming the structural curved pieces from straight strips of wood. Members of the workshop group each made an arch, using paper templates to anticipate the future method of setting out the arch curves. A CNCed template was then used to set the arches into position in space and the bracing members were added, creating the full shell. This workshop both proved the principle of the assembly method and engendered the group with a sense of ownership and understanding of the approach that would be replicated at full scale.

Complex geometries in wood are usually produced in highly specialised and expensively equipped fabricators with complex CNC or robotic machinery. This implies centralised production and therefore significant material road miles, which is a substantial contributor to the embodied carbon of most timber structures. This project presented the chance to test the other extreme, by creating a complex structure with absolutely minimal facilities and using wood sourced close to the site. All fabrication activities were carried out at the actual pavilion location hidden deep in the woodland, away from any electric power, fixed machinery, or other workshop infrastructure. The fabrication equipment was brought to the site and kept to a minimum, with only hand tools, lightweight jigs, and a wood-fuelled steaming box.

The project deploys timber ribbons in several different configurations. The primary structure is of lateral arches formed from a ladder-like sandwich of oak planks top and bottom with spacer blocks in between. These arches were each created flat, by community volunteers, on the ground at the building site to full-size templates. Towards the apex of each arch, where radiuses were too tight to cold bend, the oak planks were steam bent to allow a greater

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8. Reclaimed aluminium signage from the Forest England estates was used to form the envelope over the ridge and eyelid. © Jim Stephenson.

9. A bench is integrated with the arching structure under the 'eyelid' opening to the shelter. © Jim Stephenson.

10. The Community Shelter's inner structural layers consist of pseudo-ad-hoc bracing strips of oak that create the shell stiffness for the roof. © Jim Stephenson.

11. The Community Shelter is used for educational and special needs groups to engage in activities deep in the Westonbirt woodland. © Jim Stephenson.

curvature to be achieved. The array of these arches was held in place to form the primary skeleton of the structure; then two internal bracing layers of discrete pseudo-random laths were added to tie the arches together into a continuous shell. These 102 discrete strips were applied in two layers in opposing directions, bolted to the arches. Their layout was generated digitally through initially creating the pseudo-random flock of straight elements onto a flat plane and then mapping the end points of each to equivalent U,V surface parameter points on the target NURBS surface and creating the geodesic path between those two endpoints. This allowed the full geometry to be defined and to make sure that no clashes would occur in the actual deployment of the planks into the double-curved geometry.

The most complex elements in the structure are the four curved and twisting members, which form the edges of the two canopy cantilevers. The buildup is similar to the arches, with a sandwich of top and bottom planks with blocks in between. The geometry follows a geodesic path from the ground to each cantilever's tip. Each element required bespoke bending jigs that were set up on site. The individual planks were steam bent and then assembled by bolting into their ladder forms in the jig. Once locked in by bolting together through their spacing blocks, the edge members were temporarily supported into position, their arch members fixed in, and the shell structure completed.

The canopy is clad with cedar shingles which were also sourced from the site and produced by volunteer groups. The canopy rises into an 'eyebrow' feature on one of the sides of the building, with a bench incorporated into the space below. On the opposite side, the canopy opens with a doorway arch, formed in glue-laminated oak. The foundations are simple pads, with stainless steel upstand feet that carry a profiled oak transfer beam that supports the bottom end of each arch. The ridge zone of the roof becomes too flat for shingles to be effective, so this area is covered in aluminium panels recycled from the arboretum's old signage. Overall, through the use of immediately accessible local and recycled materials, and low-impact on-site fabrication techniques, the project's carbon footprint is small, and hopefully serves as a pointer to a localised approach to construction without compromising geometric freedom.

Conclusion

While the predominant advances in timber construction are occurring through technical improvements in the industrial production and machined fabrication of engineered wood componentry, it is also important to challenge this paradigm. Wood does not have to be treated as any other industrial product. The ubiquity and accessibility of trees, at temperate latitudes at least, puts wood in a different category to steel and concrete, whose production necessitates extensive centralised infrastructure. As shown in these projects, wood's workability allows for the immediacy of direct embodied human engagement, and for that engagement to be situated at the material source in a way that gives agency to participants in the manifestation of architecture.

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REGROW WILLOW
DIGITAL CIRCULAR CONSTRUCTION FOR EARTH–WILLOW HYBRID STRUCTURES

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The construction industry relies heavily on finite resources and follows a linear economic model of take–make–waste, causing significant environmental degradation through resource depletion and waste generation. Introducing alternative material cycles in construction could provide a solution to this impasse by enabling closed material loops, minimising waste, and diversifying material sources.

ReGrow Willow presents a willow–earth hybrid system for architectural and construction applications that enables circular material cycles through bespoke digital fabrication processes and computational tools. It incorporates lightweight, mobile, and adaptable fabrication equipment and promotes a long-term circular approach while embracing a low-impact concept that can deliver immediate reductions in energy and material consumption.

Expanding on earlier research that reinterpreted the vernacular wattle and daub material system through digital design and fabrication (Zanetti *et al.*, 2023), this research leverages willow, a rapidly renewable material that grows up to 2m annually and replenishes each year after harvesting through short rotation coppice (SRC) practices. As a bio-based material, willow can be composted at the end of its life cycle, offering a circular disposal option. *ReGrow Willow*'s objective is to demonstrate a comprehensive construction system utilising willow in combination with earth, a material that retains its recyclability indefinitely without loss of value (Morel *et al.*, 2021). The synergistic combination of these two materials, with willow serving as tension reinforcement for the earth, is advanced through tailored computational workflows. The development of customised fabrication processes hints at the scalability potential of the prefabricated building elements, while integrative digital design tools manage the interdependencies between architectural design, material systems, structural performance, and fabrication processes.

Research context

Understanding the array of construction materials available at present relies on recognising that their selection is a direct consequence of historical periods of industrialisation, leading to standardisation (Hebel and Heisel, 2017). As a result of the challenges arising from the need to achieve consistent properties for mass production or the appeal of more convenient alternatives, many vernacular materials were abandoned during earlier industrial revolutions. However, the principles of

1. Close-up of the research demonstrator. © Tobias Wootton.

customisation, aided by digital fabrication, provide an opportunity to industrialise and reintegrate sustainable, local materials, and to embrace their inherent imperfections. The ensuing diversification of construction material choices can reduce dependence on limited sources and resource depletion. This approach involves exploring processes for industrialising bio-based, renewable alternatives and substitutes for traditional aggregates.

The most notable example of revitalising renewable building materials is the recent industrialisation of timber construction, demonstrating that automation can scale up formerly manual processes, making them economically viable. This transformation can be enabled through digital workflows and robotic fabrication methods (Apolinarska *et al.*, 2016; Krieg and Lang, 2019). Industrialisation can also be pivotal in advancing innovative engineered materials like cross-laminated timber. Leveraging the flexibility of digital fabrication, timber construction can be enhanced through material programming (Wood *et al.*, 2020; Tamke *et al.*, 2021). These experiences serve as a blueprint for reintroducing naturally grown materials through digital construction technology.

Recent explorations into fast-growing renewable materials like flax, willow, and bamboo offer the potential to shift construction towards utilising cultivated resources that regenerate more rapidly than timber. These efforts involve both converting these materials into standardised industrial products, such as using willow for robotic winding filaments (Eversmann *et al.*, 2021), and exploring innovative fabrication processes and morphologies to enhance their structural stiffness (Dahy *et al.*, 2019; Eversmann *et al.*, 2021; Gil Pérez *et al.*, 2022). Another perspective involves developing methods tailored to unprocessed natural materials (Crolla, 2017). This approach promotes sustainability by avoiding additional processing stages and the associated energy consumption. It reflects principles seen in vernacular techniques like wattle and daub construction, where willow stems are used in their natural state. Leveraging digital design and fabrication's flexibility and adaptability can further enhance this approach, managing imperfections and inherent variations in the material (Devadass *et al.*, 2016; Mollica and Self, 2016; Allner *et al.*, 2020), potentially aided by artificial intelligence.

Earth is another material deeply rooted in global vernacular practices and currently experiencing a resurgence through industrialisation and digital fabrication (Schweiker *et al.*, 2021; Gomaa *et al.*, 2022). Its industrialisation has the potential to transform earth into a sustainable and circular option compared

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with conventional construction materials subjected to compression, like concrete or bricks. Examples include the industrial processes and machinery designed for rammed earth (Kloft *et al.*, 2019; Heringer *et al.*, 2022), as well as those developed for 3D printing (Dubor *et al.*, 2019; Fratello and Rael, 2020).

Bespoke fabrication solutions for natural material complexity

Due to uncharacterisable variations inherent to natural materials, building with bio-based materials – such as willow – poses unique challenges that require the coevolution of the material system and the fabrication process.

Willow stems, for example, display unique characteristics such as varying length, thickness, and strength, and the presence of knots, which significantly influence their behaviour. It is crucial to develop a system capable of handling and adapting to these variations without introducing additional processing to homogenise the material. A comprehensive fabrication system is thus established that incorporates bespoke machinery, incorporating a readaptation of industrial techniques and machinery from other fields.

To address differences in length, willow stems are initially spliced into a continuous macrofibre (Fig. 2), which is then deposited following various weaving patterns within a bed of poles by a custom-built Cartesian coordinate robot (Fig. 3). The varying thickness of the willow stem is managed by a spring-loaded, custom-made extruder that regulates extrusion speed according to the pattern. Employing additive techniques, stepper motors handle the XY motion to navigate the fabrication bed while building successive vertical (Z) layers (Fig. 2), forming a component with cell-like features (Fig. 4).

2. Willow branches are spliced into a macrofibre (left), which is woven into morphologically differentiated components (centre). Earth is pneumatically extruded at high pressure into selected cells of the willow formwork (right). © Karlsruhe Institute of Technology (DDF/dos).

3. Utilising additive techniques, a custom 2-axis machine is employed to extrude and deposit continuous macrofibres made from spliced willow branches. © Karlsruhe Institute of Technology (DDF/dos).

4. Willow component. © Karlsruhe Institute of Technology (DDF/dos).

5. Detailed design highlighting the different weaving patterns used to fabricate the willow components. The joinery system is integrated in the components and guides the distribution of earth. © Karlsruhe Institute of Technology (DDF/dos).

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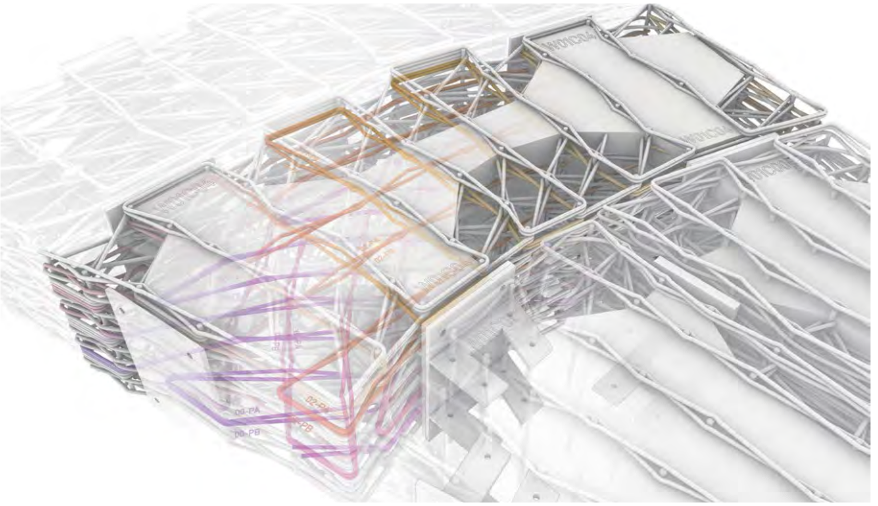

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To create the composite material, the earth is shot into selected cells within the willow formwork using an adapted plastering machine (Fig. 2). This machine employs pneumatically actuated extrusion and high-pressure spraying to compact the earth mixture and fill crevices within the willow formwork. This approach relies on geometry and the fabrication process to combine the two materials, enabling them to work together, much like reinforced concrete. In this case, the focus was on fine-tuning a range of parameters related to the earth mixture, machine specifications, and component design. The aim was to achieve compatibility between geometry and extrudability while also reducing the weight of the earth and minimising shrinkage through the incorporation of bio-based additives, like straw. Ultimately, this resulted in the formulation of an earth mixture that incorporates commercially available construction-grade materials, tailored for compatibility with the earth-filling machine.

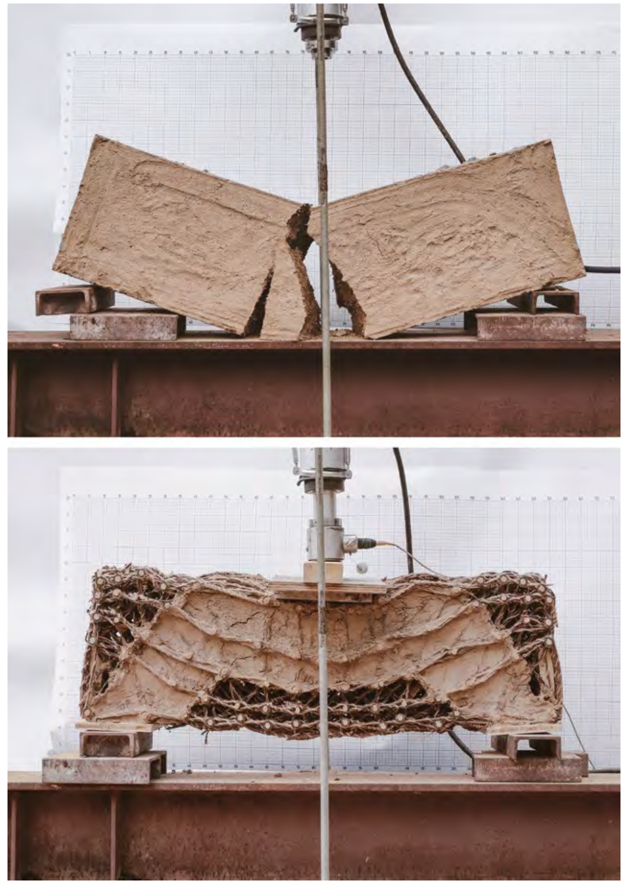
The requirement for earth to dry for at least four weeks after being cast means that prefabrication is a preferred process over on-site fabrication solutions. Prefabrication enables precise control over the drying parameters (weather protection, humidity, temperature), thus ensuring better quality.

The adaptability of the fabrication system extends beyond accommodating the unique material system. The basic principles underpinning the weaving machine's design, for example, also facilitate its scalability, thereby allowing for the scalability of the resulting building elements.

Further developments could be implemented to offer even more solutions to fabrication with the inherent variations of plant-based materials. As the willow formwork is used for its tensile strength, properly tensioning the macrofibre during weaving is crucial. However, depending on the thickness and the presence of knots, the bending behaviour of this macrofibre around the vertical elements in the fabrication bed can be unpredictable. Incorporating sensors to enable real-time adaptation and control may signify a shift towards closed-loop systems in digital fabrication to deal with inhomogeneous materials in construction applications.

Integrative design of willow–earth construction components

The development of building components is central to shaping the overall design methodology, which evolves from the intricate interactions among fabrication prerequisites, practical application, form, and overarching design considerations. The system's geometric freedom,



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resulting from the collaborative development with the fabrication process, enables morphologically differentiated elements that incorporate adaptive weaving and material placement tailored to local requirements and structural performance. Their design can vary in overall shape, cell size and arrangement, predominant weaving direction, and whether they are filled with earth. To accommodate the inherent natural variations in willow, the component design adopts a repetitive sequence of weaving patterns, embracing a redundancy-based design approach for heterogeneous materials (Fig. 5).

The resulting willow components are used for their tensile strength and simultaneously serve as formwork and reinforcement for waste-free and material-efficient earth construction. Assessing the composite behaviour of willow and earth, initial qualitative destructive testing (Fig. 6) reveals that hybrid willow and earth components demonstrate significantly increased ductility compared with earth components, enabling observable deformations before fracture and withstanding loads at least nine times greater in structural tests.

This design methodology prioritises the creation of a construction system through the development of its constituent parts. It explores an architectural language rooted in materiality and fabrication systems, leveraging the functional and intricate complexity achievable through digital design and fabrication. These digital workflows enable architects and engineers to experiment with different designs and adjust parameters to achieve specific goals while navigating the complexities of developing and implementing an innovative construction method. This approach aligns with the research goal of establishing flexible design and fabrication processes capable of accommodating diverse inputs, facilitating the integration of this construction method into conventional design and building practices. In this way, the workflows developed in this research effectively enable a digital reinterpretation of a historical material system into a modern digital construction technology.

Research demonstrator

This research is applied through the creation of a spatial structure featuring interconnected arched walls (Fig. 7), serving as a tangible representation of the design, structural, and construction possibilities. The demonstrator, located at the Federal Horticultural Show 2023 in Mannheim, Germany, showcases a series of partially enclosed spaces (Fig. 9). It also incorporates concepts of microclimatic adaptation and local energy harvesting, exemplifying a comprehensive shift towards a sustainable built environment.

The installation comprises 63 prefabricated components, with maximum dimensions of 0.80x2.20x0.4m and weights ranging from 30 to 500kg. These weight variations stem from factors like component dimensions, the earth-filling ratio, and the specific earth mixture utilised. The components incorporate a joinery system for inter-component and assembly connections (Fig. 8), enabling a relatively fast assembly process – completed in three stages, each taking two days. The structure also incorporates design-for-disassembly principles through reversible connections, signifying a shift towards an architecture that can be easily disassembled for potential reuse of its components or remanufacturing.

Computational workflows inform the material articulation and distribution in the overall structure (Casalnuovo *et al.*, 2023). This results in a material gradient, with earth primarily used at the foundations and willow prevailing at the top. This is achieved by resizing the willow cells according to the global tension-compression pattern. As a result, cells become denser in high-tension areas and

6. Tests to verify the structural performance of the hybrid components (below) compared with components made solely of earth (above). © Karlsruhe Institute of Technology (DDF/dos).

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7. View of the research demonstrator. © Christoph Engel.

8. Close-up of the research demonstrator's details. © Karlsruhe Institute of Technology (DDF/dos).

the earth-to-willow ratio is increased in areas with greater compressive stress (Fig. 1). Stress patterns determine the size and arrangement of components and guide the design and alignment of weaving patterns.

Various earth mixtures are tested in different walls, focusing on the proportion of additives like straw, significantly affecting the components' weight and structural performance. Future applications might apply a principle like gradient concrete (Herrmann and Sobek, 2017), selectively distributing different earth mixtures based on the proportion of compressive loads. This approach entails completely filling all components with earth. However, an adaptive composition of the earth mixture ensures that the increase in volume does not lead to a proportional increase in weight. Destructive tests support this configuration, demonstrating its effectiveness in reducing deformation compared to components made exclusively of willow (Casalnuovo *et al.*, 2023). Earth may also contribute to fireproofing the structure, although additional tests might be needed when using a high straw content (DIN Deutsches Institut für Normung e.V., 2018; Schäfer, 2021). Different finishing treatments are also showcased, resulting from the capabilities and constraints of the fabrication system. One side of the structure features one outer layer of willow exposed, while the other side is plastered with earth.

As weathering poses a significant challenge in earth construction, additional measures are necessary to support the construction system. In earth construction, sediment erosion can be reduced by implementing water breaks, such as protruding stone layers (Heringer *et al.*, 2022). In willow–earth structures, this can be achieved by incorporating horizontal willow patterns as the outermost layer. In future applications, weathering protection should be further improved by adopting other principles from traditional earth construction, such as using overhanging roofs to shield buildings from rain. To prevent rising ground humidity, the structure is elevated on concrete blocks. This offers further insight into incorporating circular principles within the design process, as these concrete blocks are reused elements and their dimensions become a critical predefined parameter for the structure's design.

At the end of the structure's lifecycle, the concept envisions that it can be readily disassembled, thanks to the reversible connections, and repurposed either in part or as a whole. While digital design and fabrication for bespoke components offers the potential for material-efficient construction, ultimately reducing resource depletion and transportation energy, it does not facilitate the repurposing of individual elements in different configurations. When all other options have been exhausted, the materials can be separated into earth-based and plant-based components. Earth can then be recycled for new construction, while plant-based materials can be returned to the biosphere, potentially contributing to the regeneration of new renewable resources.

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Conclusion and outlook

This research illustrates a localised approach that harnesses the customisation potential of digital design and fabrication towards the development of digital circular construction. It offers a digital reinterpretation of European vernacular architecture adaptable to diverse contexts, focusing on local solutions rooted in forgotten crafts and regional construction practices. It exemplifies collaborative development of design and fabrication strategies, alongside computational engineering, facilitating the exploration of digital construction technology rooted in historical sustainability principles and local sourcing.

The lightweight, scalable, and cost-effective machine, which can be easily moved to different locations for prefabricating components from local sources, has the potential to serve as a scalable model for extending this technique to various regions. In a wider perspective, custom digital design workflows and digital fabrication technologies may offer a model for revitalising architecture deeply tied to its environment, addressing local climate, resources, and culture. This approach can lead to a construction and architectural practice where development strategies, workflows, and open-source technologies become shared foundations, rather than a standardised global style.

This research also highlights the importance of a multi-disciplinary exploration involving collaboration with farmers, environmental organisations, and policymakers. It sets the stage for a comprehensive shift towards a local bioeconomy, as exemplified by willow cultivation on wetlands. Because of their adaptability in flood-prone areas (Roeder *et al.*, 2021), willows can be cultivated without disrupting existing agricultural zones and can function as short-term carbon sinks (Rytter *et al.*, 2015). The research has the potential to expand the possibilities and architectural language of earth construction and holds significance for the broader adoption and diversification of renewable materials in architectural applications. Future endeavours will focus on creating fully certified components that meet fireproof, soundproof, and building physics standards, and assessing their economic feasibility.

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9. View of the research demonstrator. Image: © Karlsruhe Institute of Technology (DDF/dos).

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FIBRE ADDITIVE MANUFACTURING
A CONTINUUM MATERIAL TOPOLOGY OPTIMISATION APPROACH

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Introduction

Architecture has a responsibility to seek design innovation that promotes resilience. This novel architecture, engineering, and construction (AEC) thinking is composed of the expansion of digital technologies and their applications. The result is emerging models of interdisciplinary collaboration between engineering, architecture, structural engineering, materials science, control systems, and robotics, giving shape to a domain known as design for manufacturing (DFM), a field in which additive manufacturing (AM) technology has been rapidly adopted due to its inherited benefits. This being said, the optimisation techniques presently employed in AM often overlook the mechanical anisotropy inherent in the fabrication process, leading to inferior structural properties, as they focus on layer-by-layer or 2D deposition optimisation methods. Materials that offer high anisotropy have been sparsely researched using AEC 3D printing technology, holding the potential to improve AM processes.

The potential to use fibre composites in the architectural field has sparked academic and industry interest in the past decade, prompted by fields such as automation or aerospace. This topic has been explored as a way to manufacture custom components, models, and full-scale prototypes, as notably showcased by ICD Stuttgart, ETH Zurich, and Politecnico di Milano, with fibre winding (Prado *et al.*, 2017), automatic fibre placement (Dörstelmann *et al.*, 2015), surface reinforcement (Kwon *et al.*, 2018), and continuous fibre AM (Invernizzi *et al.*, 2016). However, its further application in commercial AEC projects is limited. Although these materials and processes create significantly lightweight structures, their usage is constrained by the associated high cost of the equipment and materials, complexity, mould requirements, and so on (San Fratello *et al.*, 2020).

This paper aims to demonstrate, through two research projects, a DFM workflow to develop a lightweight, material-saving architecture for load-bearing elements using continuous fibre-reinforced plastic 3D printing (CFRP3D) composites without the inherited difficulties or costs associated with those materials or their materialisation. The study investigates the advantages of using continuum material topology optimisation within three-dimensional non-standard lattice structures through integrated AM processes. Traditional spatial lattices,

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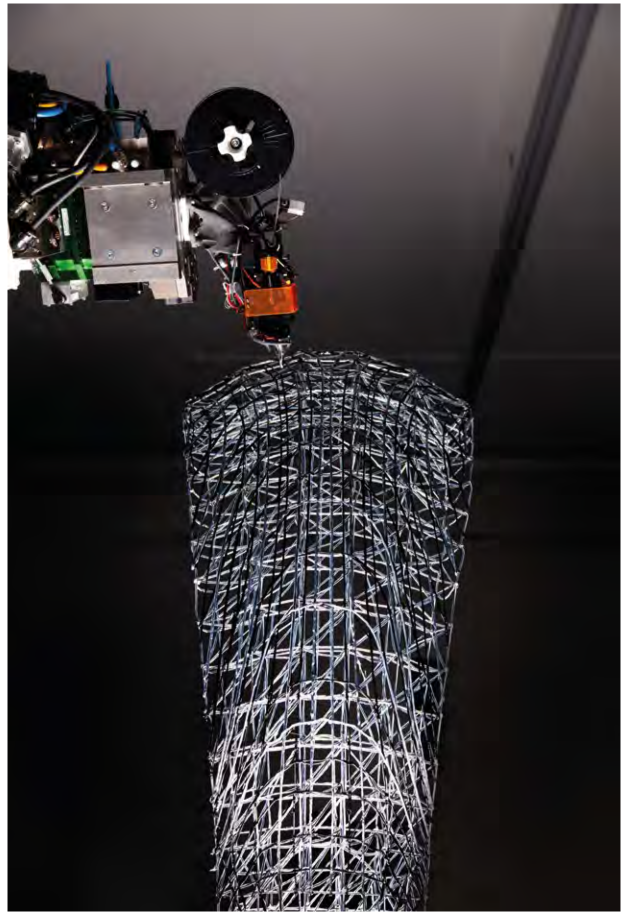
1. Regular cell print of unsupported element.



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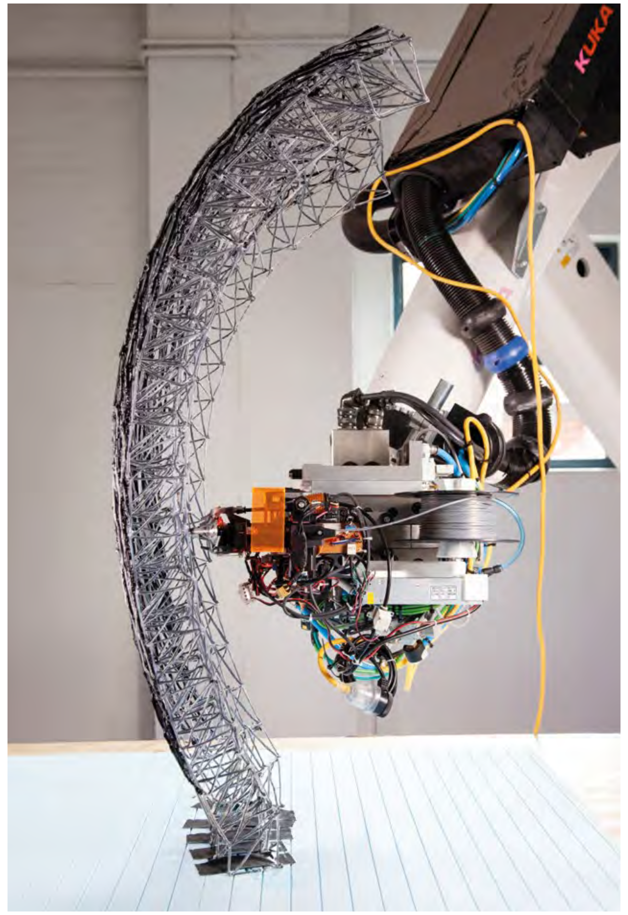

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known as spaceframes, have long been used to maximise structural efficiency by enhancing flexural rigidity and load-bearing capacity while minimising material usage. Lightweight and high-performing load-bearing structures can be achieved by employing specific non-standard lattice geometries.

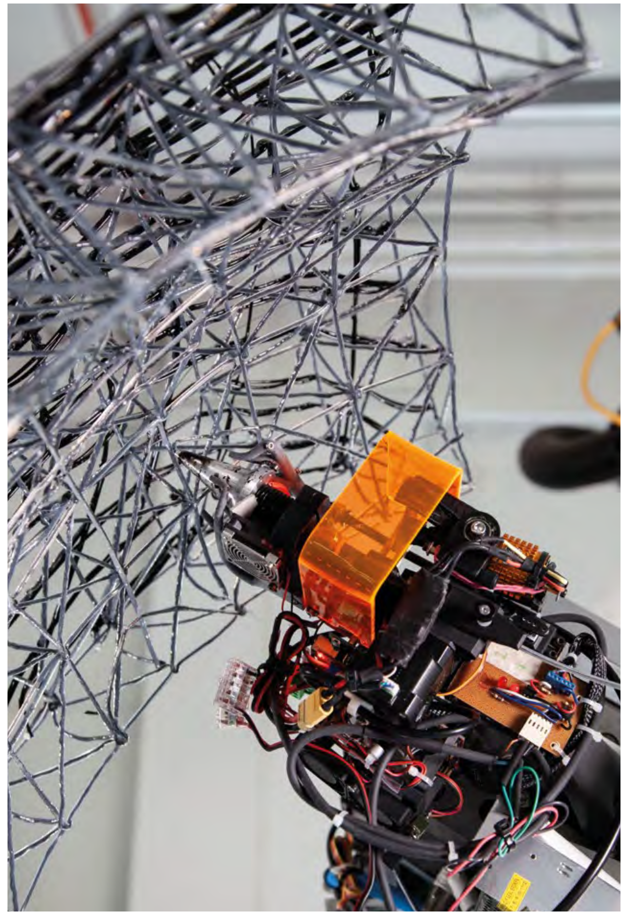
Technicality: CFRP3D end-effector

Unlike previous continuous fibre deposition techniques that rely on a mould or base structure, this extrusion technique has similarities to fused deposition modelling, but offers dramatically larger overhang capabilities (Eichenhofer *et al.*, 2017). This particularity enables novel functionality, including printing in the air and start-stop printing, which is imperative for complex topologies. Unlike short fibre AM, depositing a continuous strand of fibres offers great structural benefits, but, inherently, the toolpath sequencing raises some concern (Figs. 3, 4).

The use of CFRP3D for manufacturing involves employing a six – or more – axis platform, as the fibre inherently needs to be able to be oriented along or opposite to the loads to maximise its usage. In our work, industrial robotic arms from Universal Robots and KUKA, specifically a UR10e and a KUKA KR120, were used for the fabrication of Case Studies 1 and 2 respectively. The fibre composite used consists of three compounded dry carbon rovings combined with a matrix material. The specifications of both case studies are Tenax® with HTS40 F13 / 12k / 800 tex and PHA/PLA for the matrix, which offers a better Young's Modulus ratio than other similar PLA products. The ad-hoc end-effector can handle a variety of thermopolymer matrix materials, enabling it to adapt to multiple architectural scenarios, from highly flexible materials such as PTEG to high-strength and fire-rated ones such as polycarbonate (Snooks and Harper, 2020). Even so, this CFRP3D process could theoretically be used with any thermoplastics matrix with an adapted end-effector. The ad-hoc tool combines threads in the collimator, which executes a mixture of temperature and

2. Robot depositing continuous fibre along the stress lines on Case Study 2 canopy.

3. Robotic arm CFRP3D reaching the interior face of the lattice canopy of Case Study 2.



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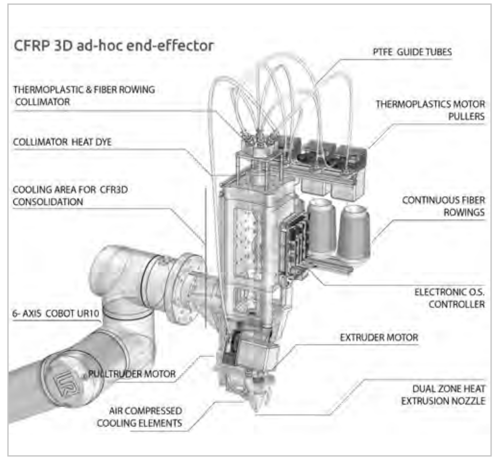

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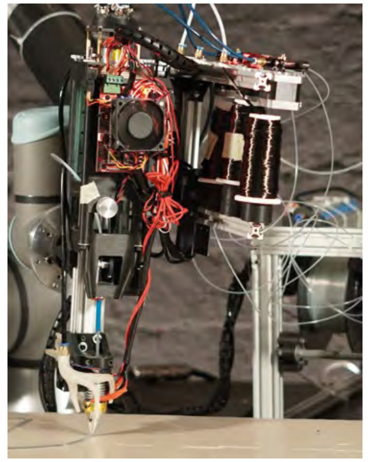

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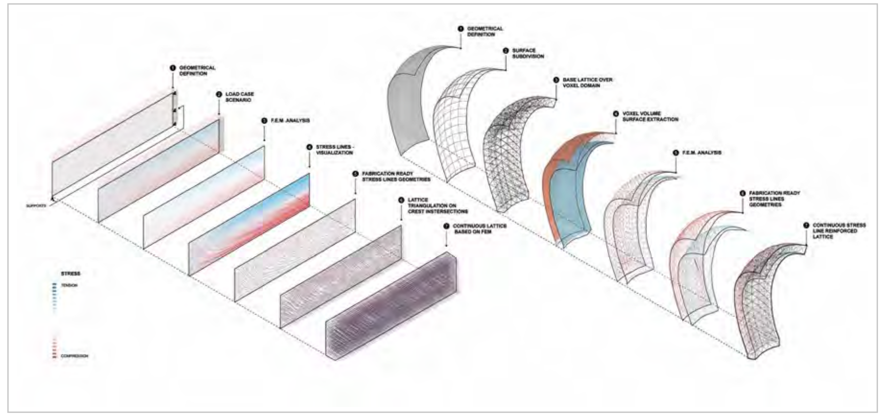

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pull-pressure dragging of the fibres (Eichenhofer *et al.*, 2017) to later re-extrude the final composite; this tool uses a pultrusion re-extrusion technique to combine the material in real time, as depicted in Figs. 5, 6. As the PHA/PLA matrix material is used for these probes, it is not considered a high-specification technical mixture plastic such as polycarbonate. Thus, it offers the possibility to be used without any special requirements, such as a controlled temperature environment, heated base plate, or other considerations like retraction or warping.

Flowing forces

There were three primary objectives in the development of the DFM strategies used in this research. First, for structural reasons, translating the finite element analysis (FEA) structural force flows into a line geometry, which is commonly stipulated as stress lines. Second, accommodating the manufacturing constraints inherited from the process, such as a minimum distance between lines due to end-effector dimensions, approach angles, and so on. Third, achieving material usage reduction while still having structural compliance for the original accounted design scenario. In contrast to conventional computer-aided design and computer-aided manufacturing (CAD/CAM) workflows, the structural generation modelling algorithmic workflow adopted uses FEA as a base to generate fabrication-ready geometries. Stress-line generation is usually a visual tool used in structural design softwares such as KARAMBA 3D. This is an FEA plugin for Rhinoceros 3D and Grasshopper 3D modelling environment tools, which were used in this study. The data and geometrical stress-line generated by these tools are not feasible for fabrication and need to be heavily post-rationalised. The stress lines generation and the computational algorithms used to generate printable geometries are therefore based on existing research on the topic of AM (Tam *et al.*, 2016) and extensively characterised in Chamorro *et al.*, (2023).

These optimised continuous material flows are intricately woven into spatial lattice structures (Case Study 1) or

4. Interior topology and image detail of end-effector of Case Study 2.

5 & 6. Diagrammatic technical drawing and image of the custom pultruded-extruder end-effector used in Case Study 1.

7. Description of the generative methods 'form-found' or 'free-form', as used in Case Studies 1 and 2 respectively.

projected into a lattice (Case Study 2), resulting in enhanced material efficiency and improved structural performance when compared with homogeneous lattices. The inherent flexibility of AM allows for the creation of aggregated continuous truss-like elements. The combination of continuous line geometries based on structural behaviours, together with the interconnecting elements, results in a variation of the cellular topologies, which respond to structural needs (Fig. 8). This process enables the deposition of materials without the need for moulds, complex fabrication rigs, or a vacuum-assisted moulding process, among others, as the equipment needed is reduced to an end-effector, a robotic arm, the dry fibre, and the matrix materials.

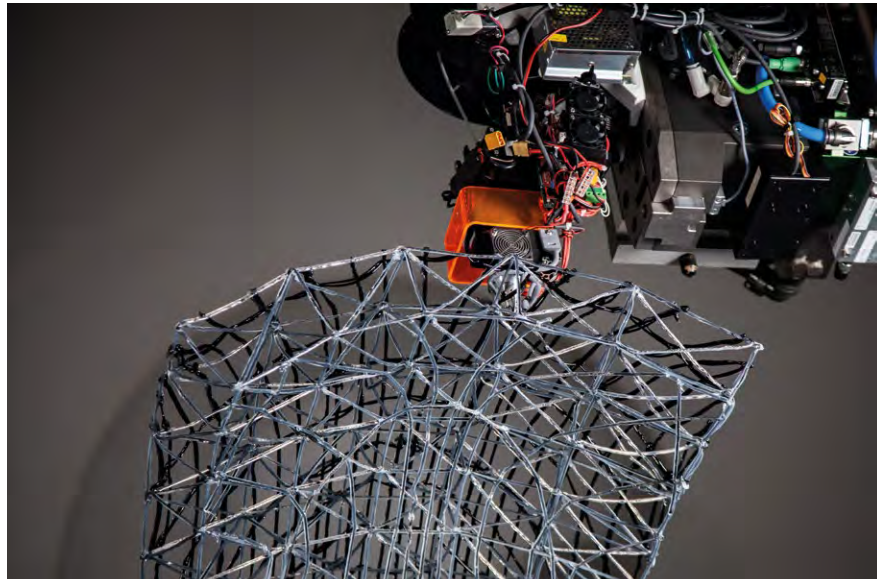
In both cases, it was necessary to establish a predictive model on the material behaviour that largely depended on fibre-matrix percentage, element thickness, and element length. This resulted in many early linear prototypes of simple measurable profiles and length uniformity that were experimentally characterised by tension and compression testing in computerised load-press machines. Moreover, to overcome issues such as single-member buckling, we employed experimental data acquisition methods via optical metrology, 3D scanning, and thermal imaging. This approach allowed us to establish the boundaries of the material-to-manufacturing specificities.

Integrated design for manufacture

This printing technique led to two opposite design logic workflows for structural experimentation: i) a FEA lattice-driven design method and ii) a surface-to-lattice design translation. The opposite strategies used in this research could be categorised as ‘form-found’ or ‘free-form’ as per Case Studies 1 and 2 respectively, each one with its inherited benefits and constraints.

Case Study 1: Form-found

To initially validate the proposed ‘form-found’ approach, a first case study with a bridge-like geometry was designed and fabricated. The prototype followed the standard structural scenario of the Messerschmitt-Bölkow-Blohm (MMB) beam problem. This was designed to withstand a maximum distributed load of 4kn/m^2, with the physical prototype measuring 2x0.25x9m and weighing 3.88kg (Fig. 9). A 6-axis Cobot equipped with a custom end-effector for continuous fibre impregnation was employed for the fabrication process. This deposited material at 225°C to enhance the matrix bonding between elements, a temperature at which the matrix material was in a semi-liquid state and being held in position by the tension of the fibres. The deposition was executed at feed rates of 8mm/s and actively cooling the printed elements with a pneumatic system ejecting an airflow of 2.5 bar at the nozzle.



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8. View of the internal and external stress lines of the lattice model and material deposition for Case Study 2.

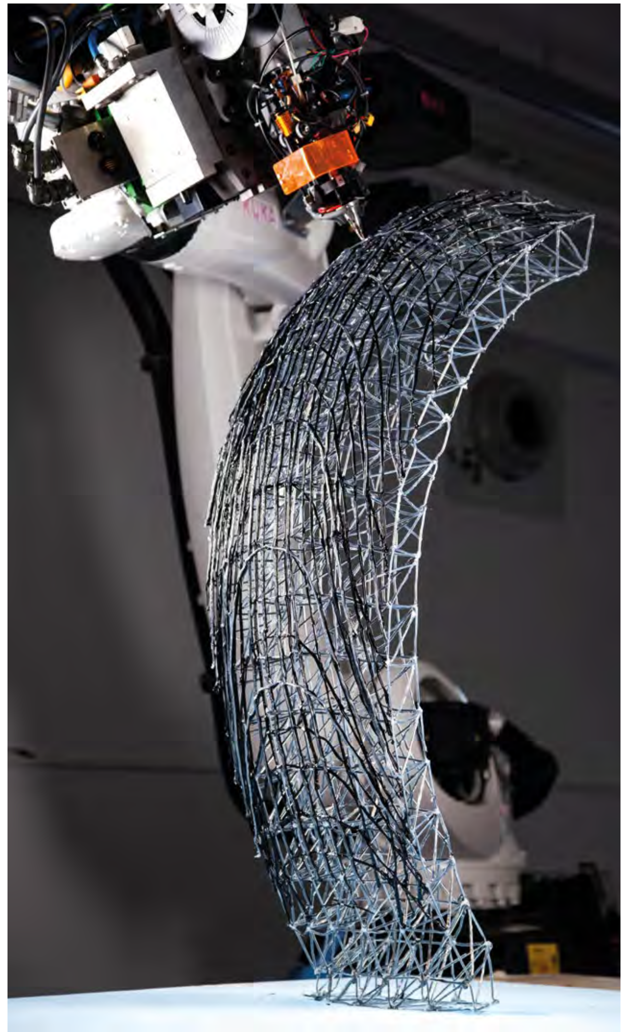
9. Case Study 1 showing structural optimisation based on spatial lattice stress-line geometries with continuous fibre-reinforced plastic 3D printing AM technology.

The proposed approach to generate printable paths used in this scenario creates the stress lines over the bidimensional design domain established in the FEA. This is executed through a series of recursive algorithms in which the result is a two-dimensional polygonal grid. This grid is then connected to its corresponding projection on the z-axis at the intersections of cross-members on each vertex. The resulting three-dimensional lattice structure is formed both in-plane and within the weaving arrangement. The sizing of individual cells is determined by the manufacturing criteria, specifically maximum and minimum spacing in the generation of stress lines. This results in variations in cellular topologies that adapt to structural requirements.

Case Study 2: Free-form

This probe was manufactured with the same materiality as Case Study 1: Form-found, but in this scenario, the composite material was priorly prefabricated and fed into a later iteration of the Case 1 end-effector. This one separates the material combination stage to form a commingled composite from the deposition one. This change allows for an end-effector with a smaller footprint, higher reachability inside the lattice, selectively stop and start printing capabilities, easier transport and integration of an automated cutting mechanism for the fibres. The deposition was executed at feed rates of 25mm/s with a theoretical deposition speed of the system of 100mm/s.

This case study is a double-curved canopy (Fig. 10), generally designed to showcase the larger freedom of shape of this CFRP3D technology compared with similar ones, such as continuous fibre winding, which is constrained to ruled-surfaces models, single-curvature ones, or anticlastic surfaces (Bodea *et al.*, 2022). The canopy with 140cm height by 65cm width and 45cm cantilever was initially free-formed by a lofted surface, which was designed to be aesthetically pleasant, not taking any initial structural or manufacturing constraints other than the initial work cell space of the robotic arm in use. The UV surface design space was topologically divided into an evenly numbered voxelised matrix, conforming to regular tetrahedron struct-lattice cell topology. This consisted of a single-row matrix for the surface normal and an equally distributed UV division on which the stress-line trajectories were generated following the form of the top and bottom sides of the matrix surface.



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10. CFRP3D double-curved canopy.

The dimensions of the surface-to-cell divisions were determined by the preliminary maximum span capabilities of the extruder, which for this tool configuration was stated at a minimum spacing of 20mm because of manufacturing constraints and a maximum reach of 160mm (Fig. 1) due to structural limitations. The resulting double-curved surface had a voxel cell normal thickness of 80mm and UV cell dimensions stated in the range from 80mm to 150mm, as the surface was heterogeneously divided. The cell lattice topology was reanalysed as a shell to extract the stress lines on the volume, which were later printed. Total linear material usage for this model was 129m of continuous fibre composite with a total weight of 1.9kg, with a required print time of 40 hours for the whole element. Stress lines printed on the exterior volume of the lattice were tinted with a black pigment to give visual emphasis to their trajectories.

11

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Aside from the human-related operating errors on the different toolpath files in which the manufacturing sequence was divided, the predicted deviation from the physical model manufacturing due to miscalibrations, extrusion to feed rate mismatch, and material sag, provided overall good results, as most of the lattice nodes were reached multiple times from diverse positions and angles, resulting in an error deviation below 2mm. Nevertheless, the system will benefit from a closed-loop system in which the tension of the fibre on print is being monitored at the nozzle as a modifier of the robotic platform feed rate (Fig. 11).

To test how the resulting structure carried the initial structural design scenario, linear elasticity simulations and analysis of the models were executed on both case studies, with the line geometries used for the manufacturing toolpath. The cross-section resulting from the AM method used produced a 4mm-diameter element, which was introduced in the simulation as the individual beam dimension. Moreover, a comparison analysis was executed of a fibre model versus a non-fibre one.

The fibre models inherit the material performance values already researched by Zhuo *et al.* (2021), being a Young's Modulus of 5000kN/m^2, (50MPA), an In-plane shear modulus of 2000kN/cm^2, a combined specific weight of 17.45kN/m^3, and the rest of the anisotropy characteristics for the mixture of carbon fibre dry rowing and PHA/PLA matrix composite (Fig. 12). The simulation of the resulting structure showcases a clear benefit from the fibre materiality with significantly less deformation and a clear under-utilisation of the elements in tension.

Thus, to accommodate possible fabrication constraints or simulation validity, two 1:2-scale models of 1m span were structurally tested through destructive testing for data validation (Figs. 13, 14). On top of this, a large set of individual linear rods and unitary cells were also tested for compression and tension. Verification of the mechanical performance of the methodology is a critical aspect of it. The results from the test showcase a three-times-higher carrying load capacity of the fibre model with reduced deformation corroborating the simulation results, with the models breaking by individual member buckling of the elements at compression.

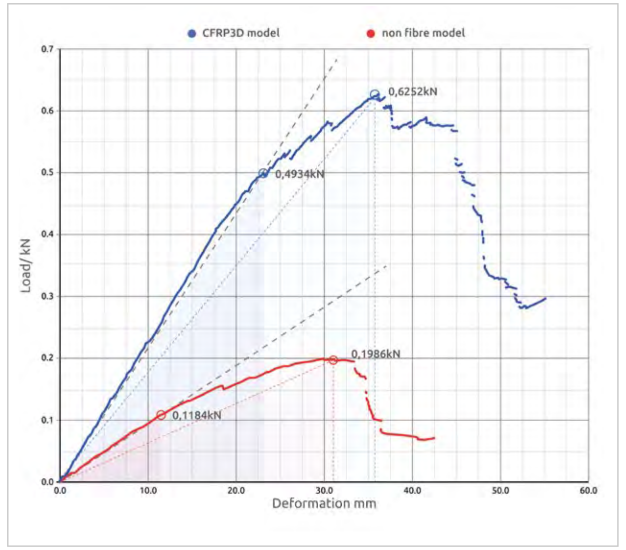
Conclusion

In conclusion, the aim of this research is to illustrate the potential of technology adoptions such as CFRP3D, together with computational design workflows, to maximise structural performance with minimal material usage and zero-waste techniques towards more sustainable and optimised construction elements. Achieving effective and efficient use of materials in architectural practice requires harnessing composite material capabilities while taking AM constraints into consideration. Using a DFM method that prompts reflection on how we can reshape fabrication to meet resource and material economy challenges, as well as respond to material optimisation, this research attempts to open radical departures in architecture structural design.

Since the focus of this research was a computational and manufacturing workflow associated with materiality, standard industry carbon dry fibres were used. There is

11. End-effector tool depositing material in mid-air while reaching a lattice node.

12. Front view of the CFRP3D in Case Study 1, covering a 2m span, with a person standing on top.



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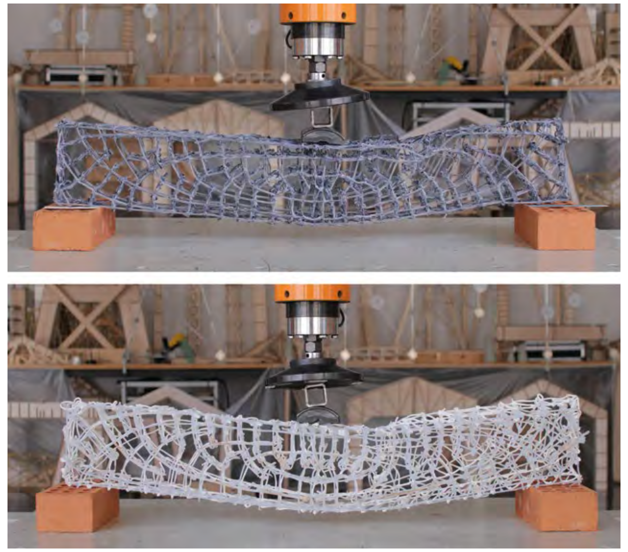

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13 & 14 . Three-point load computerised press test over a grey model made of PLA + continuous fibre material, and a white model made of PLA with non-fibre content. The graph showcases the load vs deformation curves of both tests.

room and opportunity for the exploration of alternative sustainable fibre materials such as flax or hemp fibres and other bio-based thermoplastics for the matrix component. The method by which the lattice is established, results in extremely complex arrangements and intricacies that could be employed to provide internal support, in concrete sprayed foam or other light-volume filling materials such as expanded foam. These could use the lattice as a high-performance re-bar-like structure and open-form support mould. The case studies presented in this paper can contribute to the discourse on building DFM culture as a globalised practice in AEC.

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WEAVING THE SHIMONI CAVE
AMPLIFYING CRAFT PRACTICE THROUGH COMPUTATION

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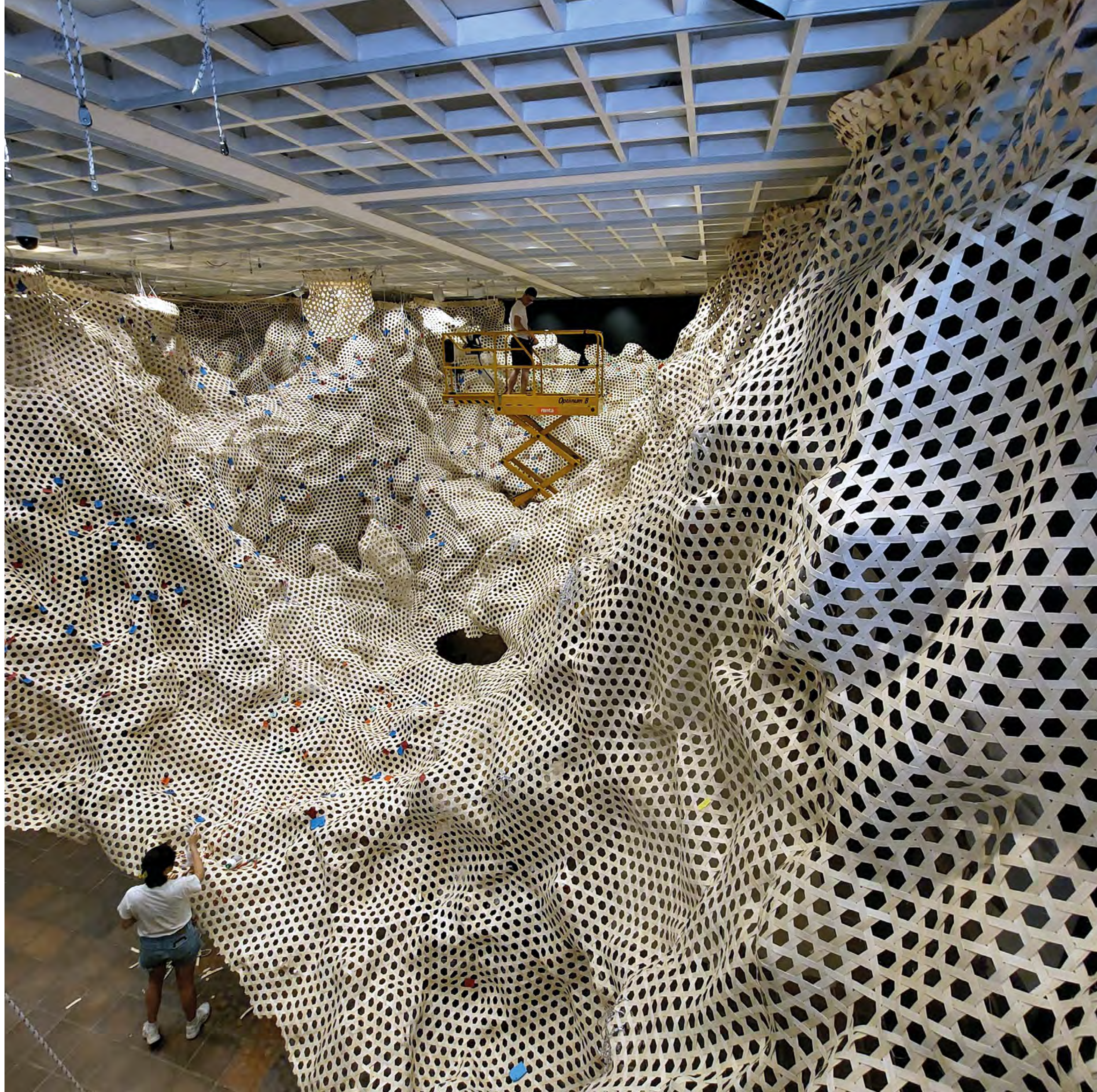
Introduction

In this paper, we demonstrate the application of the Kagome basket weaving technique to realise a 300m² near-net approximation of a complex, free-form geometry, hand-woven from approximately 350kg of low-impact, renewable material that is fully recoverable. The project showcases the potential of computation to amplify this craft across dimensions of geometric scale and complexity – thereby widening the domain of applicability beyond its humble basket origins (Fig. 1). More broadly, the project draws attention to the value of this ancient knowledge, not in an anachronistic or romantic way, but acknowledging it as a reservoir of deep innovative potential that holds relevance to contemporary challenges where material impact, material intensity, and material reuse are in sharp focus.

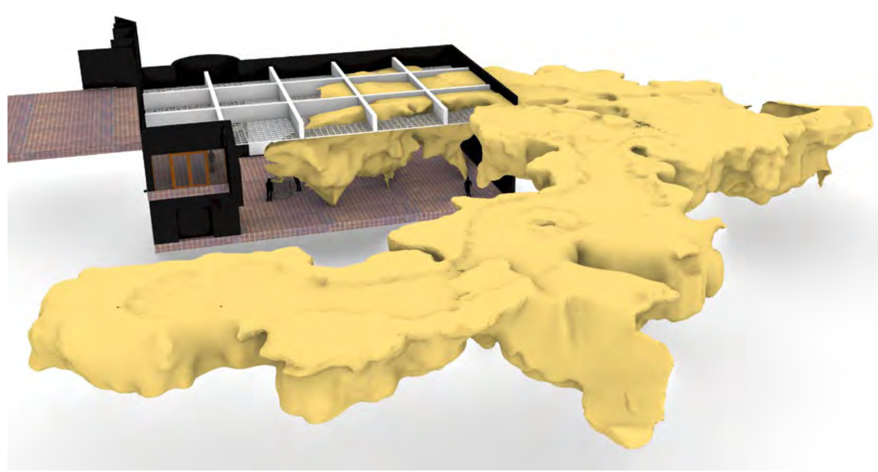
Through this technique, near-net approximations of arbitrary manifold geometries can be rationalised and realised with regular, straight stock materials. Importantly, this can be done without advanced industrial and digital manufacturing technologies, rendering geometrically complex forms possible without the need for bespoke fabrication techniques.

Context

In September 2022, the Louisiana Museum of Modern Art, Denmark, invited the Nairobi-based architectural practice Cave_bureau to produce the sixth and final exhibition in its Architect's Studio Series. Cave_bureau operates within the anthropological and geological context of the postcolonial African city. Through strategies of translation and transposition, sites with difficult histories are sensitively interrogated and reconfigured into architectural propositions that simultaneously expose these histories, while seeking avenues for moving forward that privilege the rights of indigenous communities. The Shimoni caves, located 75km south of Mombasa, are a principal site of reference for Cave_bureau. The caves act as a location for anchoring an African origin narrative for architecture. This counters the dominant European narrative of Laugier's Primitive Hut as a fabricated artefact of human projection and endeavour. Rather, it constructs a nuanced and inter-relational perspective that situates the first acts of human habitation as anchored to the earth, embedded within geological timeframes, and inherently reciprocal. The Shimoni site is a setting that has witnessed decades of trauma, having been used as a holding area for hundreds of thousands, if not millions, of African slaves, who were



1. The Shimoni cave is a 300m² Kagome weave that demonstrates the amplification of this craft through the application of computation. © Phil Ayres, Royal Danish Academy.



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2. Exhibition concept for introducing the Shimoni caves into the Louisiana Museum's Store Sal. © Cave_bureau, Nairobi.

3. Various representations that serve different fabrication and communication purposes. From far right: 1) the principled topological tri-mesh, 2) the dual graph of the mesh, 3) the medial construction mesh, and 4) the skinned mesh. © Jack Young, Louisiana Museum of Modern Art; Phil Ayres, Royal Danish Academy.

4. Representation of the weave in position within Store Sal, rendered with 20mm flat rattan members. © Jack Young, Louisiana Museum of Modern Art.

5. The dual graph representation of the weave, showing the singularities as coloured polygons and modelled without direct adjacencies. © Jack Young, Louisiana Museum of Modern Art.

shipped from the East African coast to slave markets in Zanzibar and on to Yemen and the port cities of the Middle East, during a slave trafficking era that reached its peak in the later 19th century.

As part of its exhibition proposal, Cave_bureau sought to transpose a 1:1 portion of the Shimoni caves into a museum space known as Store Sal. At approximately 20m in length, 15m in breadth, and 6m in height, Store Sal is the largest of the museum's internal exhibition spaces. The concept was to use Store Sal to 'cut' a fragment of the cave geometry, giving the appearance of the cave extending beyond the containing boundary (Fig. 2). In October 2022, the Centre for Information Technology and Architecture (CITA) was approached to explore how such a vision might be fabricated. In discussing the broader intentions and theoretical framing of the exhibition, it became clear that, while employing advanced industrial methods of digital fabrication could lead to a high-fidelity rendering of the Shimoni caves, such an approach would not resonate with the subject matter constituting the exhibition – particularly those aspects dealing with the historical and contemporary forces that continue to impose conditions of precarity upon indigenous communities.

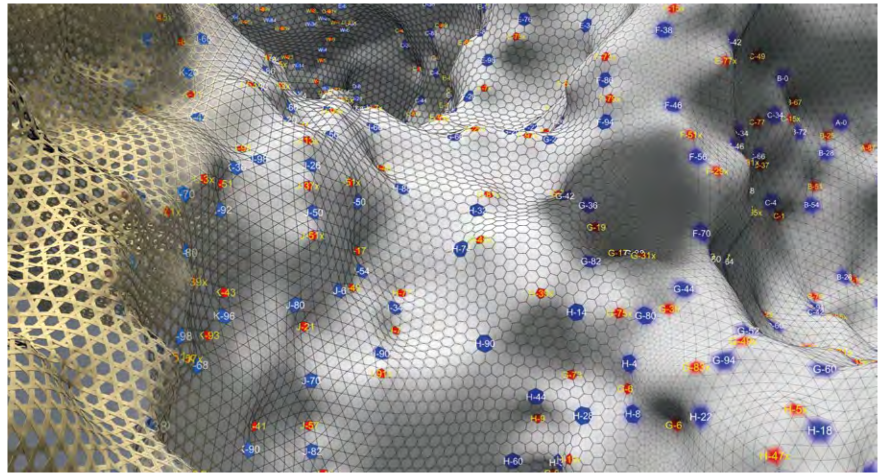
Drawing on significant advancements in the digital representation of Kagome weaves within the context of the EU-funded Fungal Architectures project, it was proposed to weave the cave. With a pre-industrial provenance, this weaving technology resonated with the discourses surrounding decolonisation. In addition, it foregrounds ideas about indigenous knowledge having contemporary value in the search to devise courses of action to address the entangled crises of the present (Watson, 2019). The agreement to proceed with the Kagome weaving concept offered a unique opportunity to apply and evaluate our Kagome weaving research at a geometric scale and complexity not yet approached, with the acid test being if the calculated placement of singularities from our digital workflow would indeed produce the local, meso, and macro-scale geometric features of the design target.

Two workshops were planned for December 2022 and January 2023, with the main focus being the training of weavers, preparation of materials, and specification of a remote working space within one of Louisiana's holding warehouses. Weaving of the cave commenced properly at the start of February 2023 and would continue off site for three and a half months. The weave was then transported in large sections to the museum and installed over a period of six weeks.

Kagome weave and developments in digital representation

Kagome is a traditional sparse-weave handcraft for making baskets from locally available fibrous materials. This material interlacing technique is based on a trihexagonal tiling which, if followed systematically, results in regular planar weaves. However, a fundamental property of Kagome technique is the ability to induce double curvature into the weave by introducing singularities into the regular lattice. A singularity refers to a hexagonal cell that has been exchanged for an alternative polygon. Introducing a lesser-sided polygon induces synclastic (positive gaussian) curvature, whereas greater-sided polygons induce anti-clastic (negative gaussian curvature). This provides the basis for achieving near-net approximations of complex morphologies, including high genus shapes, using straight stock materials. This combination of material interlacing in a triaxial configuration with the ability to induce double curvature yields highly resilient structures that effortlessly integrate functional utility with potent aesthetic qualities. These attributes make it an interesting – and potentially impactful – target for exploration within an architectural context.

We have previously reported on the development of digital design tools for generating principled Kagome weave patterns (Ayres *et al.*, 2018), based on the Medial Construction method (Mallos, 2009), and extended into a mesh topology adjustment scheme (MTAS) (Ayres *et al.*, 2021). MTAS facilitated user modification of the underlying topological graph, providing the basis for weave representations and fabrication data to be generated. However, MTAS had a series of limitations.



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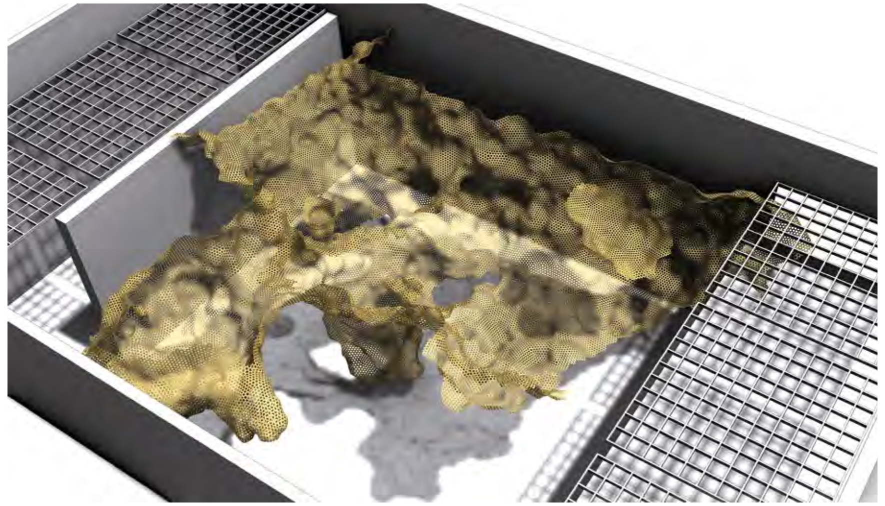

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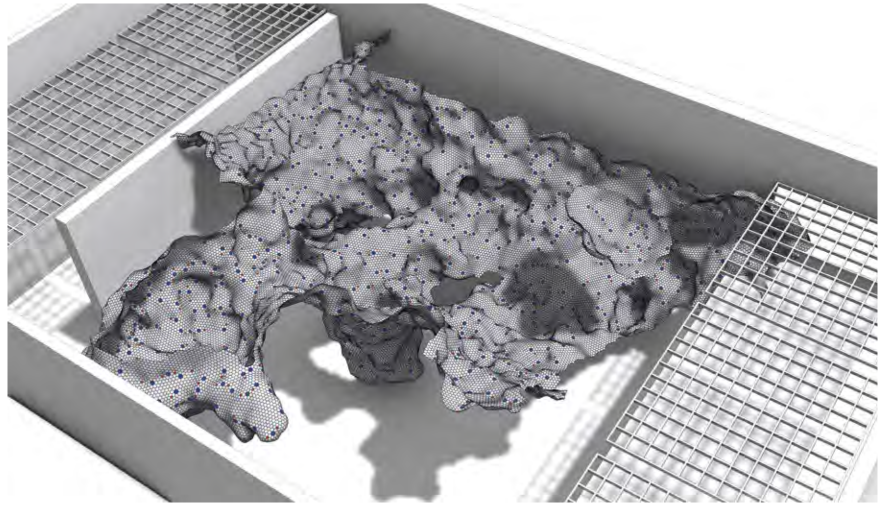

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These included:

1. Manual locating of vertices for topology adjustment.
2. Sequences of singularity placement potentially resulting in failed topology designs despite being physically weavable
3. Closed geometries failing due to circular dependencies in topology adjustment.
4. Strong design intuition being required to produce complex weave pattern designs to approximate desired morphologies, due to regular planar tri-mesh being used as the basis for the method.

The work presented here benefits from a significant overhaul in our approach to generating weave pattern topologies. It addresses the limitations cited above and provides an automated and generalised approach for weave pattern generation that can be applied to different input data sets. Central to this revised scheme is a remeshing procedure using a Target Edge Length (TEL) constraint. This is a 'topology-finding' procedure, analogous to performing a sphere-packing on the target geometry. This generalised procedure will generate a principled topology for any geometry that can be described by a manifold tri-mesh. This opens a rich design space for Kagome craft and its potential for application beyond basket-making. From the principled topological mesh, three subsequent representations are produced to support fabrication and communication: the dual mesh, which serves as the principal guide for weaving as it allows easier correlation and navigation within the lattice; the medial construction mesh, which generates the actual Kagome pattern; the skinned mesh, which models the interlacing and the stock material (Fig. 3).

Material considerations

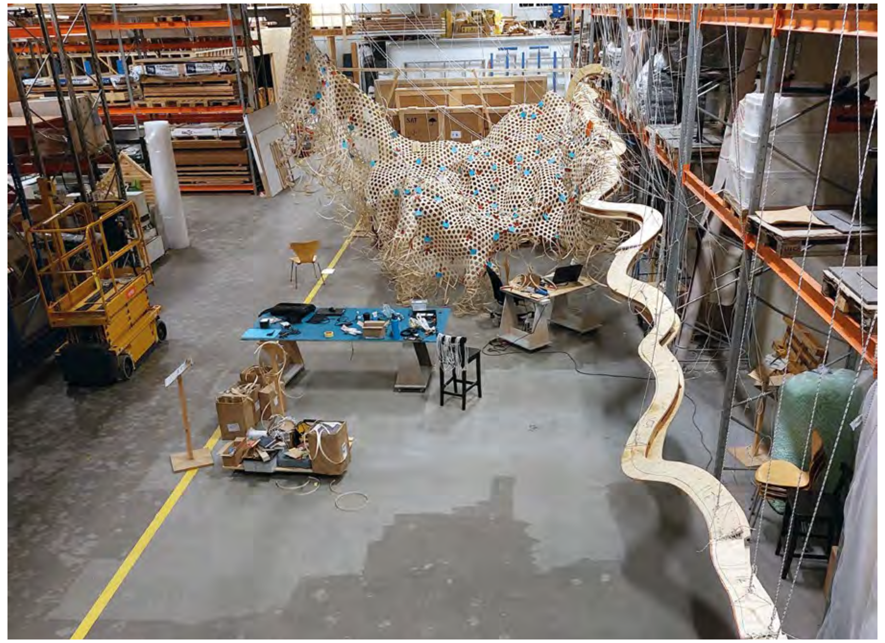
Rattan is a light, strong, vine-like palm that grows across Southeast Asia and Africa, with more than 70% of the present global supply coming from Indonesia. It is fast growing and replenishes every five to seven years, usually reaching between 6 and 10m in length before harvest, though in the wild, stems extending to hundreds of metres have been found. Although technically processed to produce flat strips, this natural fibrous material exhibits heterogeneity and imperfections that can give rise to a wide variability in quality and mechanical properties. This variability is managed continuously by the weaver, at the point of weaving where poor quality material is quickly identified and can be substituted. However, the resilience and redundancy of triaxial weaving is extremely accommodating, both structurally and aesthetically, which means that condemned material can be minimised.

For Kagome weaving, rattan flat is preferred, as this provides increased surface-to-surface friction at the weaver crossings compared with other material sections. The material supply is offered in a range of widths of 1mm thick flat, from 4.5mm wide to 25mm wide, with strips bundled in coils of 0.5kg. The choice of width has a direct bearing on the density of the weave, its 'cover' ratio, the length of material required, and, ultimately, the total mass of the weave. Regular physical weaves were made using 12, 16, 20, and 25mm rattan flat widths to determine an average weave density for each. The physical study also provided additional metrics on the total length of material in a coil, the average number of individual strips in a coil, and their length distribution – which could vary between 1 and 4.5m. These metrics were used to inform a series of digital studies through which to determine the choice of 20mm-width material – a decision that balanced considerations of visual effect, total number of cells (implicating weave time), total mass, and stock availability (Fig. 4).

Digital design and fabrication strategy

A lidar scan of the Shimoni site was provided, and the target region extracted, cleaned, and rebuilt into a regular tri-mesh that minimised angular deviation around each vertex. This was then relaxed to alter the topology until the resulting geometry approximated the target geometry as closely as possible using the TEL constraint. This initial remeshing was done at half the resolution of the final weave so that it could be subdivided to ensure singularities were not adjacent (Fig. 5). While meshing with the actual weave size would allow the output to conform more closely to the target geometry, singularity adjacencies cause large local buckling in the weavers. In regions with strings of alternating adjacent valence 5 and valence 7 singularities, the cell sizes are difficult to keep uniform and will either warp the resulting geometry or cause it to buckle as the material exceeds its minimum bending radius. This will cause a weak area, which is prone to deformation over time.

Kagome weaving is systematic – at the point of material interaction, the interlacing logic is a given. The fabrication strategy therefore focused on how to manage production, where production would occur, data segmentation and transfer from the master model to the weavers, logistics, scheduling of production milestones, and developing methods of calibration and feedback between the built and the master model to ensure a minimisation of deviation. The production window was set at just under five months, starting in February 2023 and running up to the public opening on 29 June, 2023.



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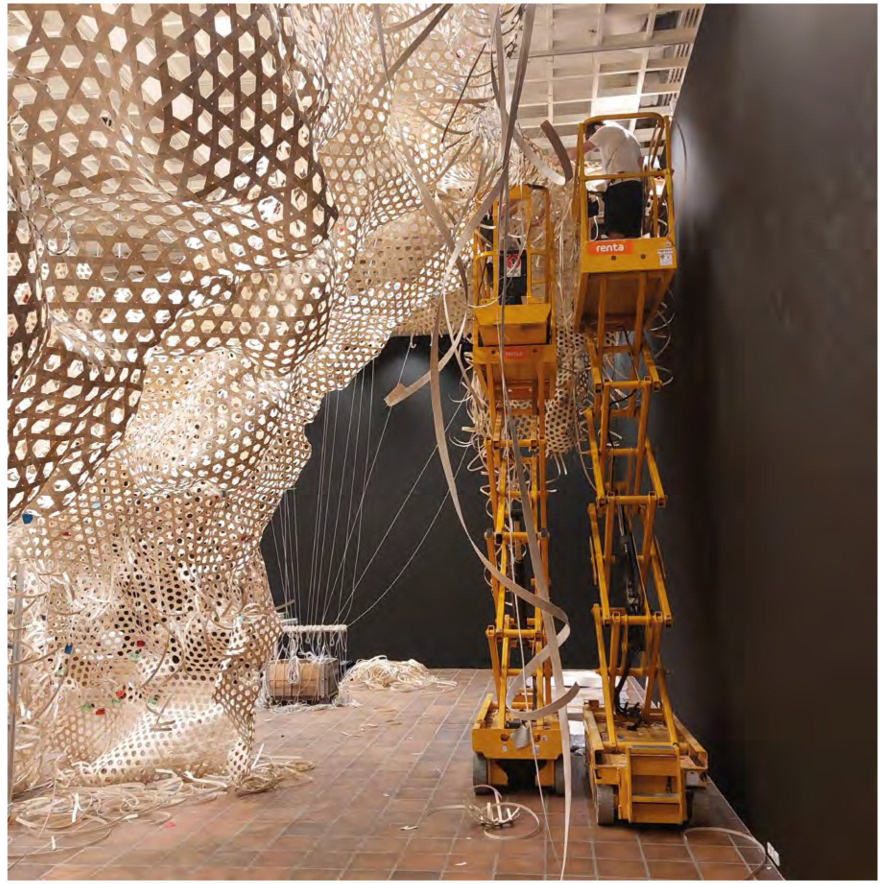

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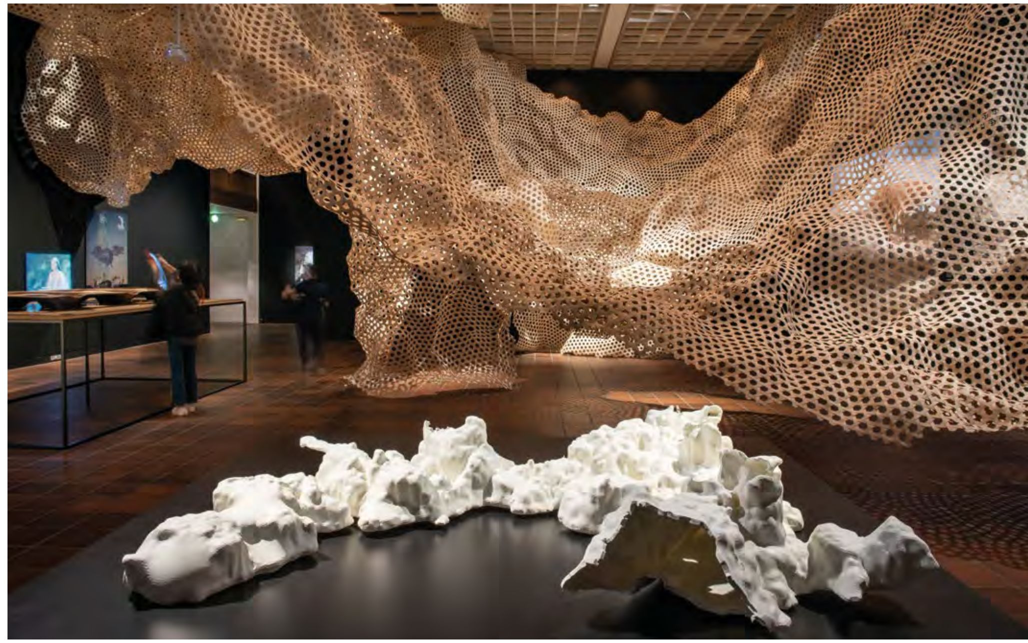
Store Sal would not be available until mid-May, so most of the weaving had to be produced off site. Moving the weave as a whole would be unfeasible, so it was decided to segment the cave into three large patches. In practice, segmentation is complicated by the fact that weaving is a manual process with a high degree of local variability. Two sections woven separately are unlikely to perfectly align due to small cumulative differences in weaving style. To account for this, the three patches were woven with a gap of at least six cells between them. This connective and accommodating region would be woven in-situ at the museum.

To regulate the weave's production dimensionally, a method of calibration was devised. While this could have been done digitally, the technical, logistical, and financial overhead could not be reconciled against the simplicity of using a physical guide. The guide was found from the embedding of the cave in Store Sal, which resulted in three different interface conditions: the ground (ceramic floor tiles), the walls (stud-frame), and the ceilings (an open steel grid with incorporated power and lighting). The walls and ceilings were literal section planes, producing a complex contour in the weave. Cutting this contour and marking indexed singularity placements provided immediate feedback to the weaver for regulating weave density. The rail also doubled as a rigging member, which could be continuously hoisted to ensure that weaving could be conducted at a height to maintain comfortable posture (Fig. 6).

The master model was segmented into smaller patches to be issued to the weavers on iPads running Rhino. These sub-models were issued using the dual graph representation of the topologically principled base mesh, removing detail and rendering the lattice as polygons. All singularities were given a unique index, critical for orientating and navigating within a patch. To correlate between patches, the sub-models included large overlaps to assist orientation between one patch and its neighbours. It was essential to implement this robust method of orientation rather than relying on visual features, as the weave can look vastly different from the digital model during weaving. The indexing approach facilitated the ability of weavers to be autonomous and quickly take up ongoing weaving work anywhere on the weave with minimal orientation time – essential, as many of the weavers worked part-time. The correlation between the digital and physical weave was found by identifying the closest singularity to the working edge, then tracing the most direct path to existing neighbouring singularities. Physical index tags corresponding to the individual digital address were placed on the weave. From this



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triangulation it is possible to understand the correct orientation and determine how many more cells need to be added, and in which direction, before another singularity is introduced.

The risk with a fully predetermined model at the level of complexity and topological dependency seen in the cave, is that a single misplaced physically woven singularity will make all unwoven topological information redundant. A physical deviation will cause a rapid drift away from the topological map, the implication being that the weaver is unwittingly embarking on the production of an alternative morphology. Fortunately, the indexing approach and orientation through triangulation embeds an inherent check. Mistakes are found within one or two singularity introductions, as the cell distance to neighbours will no longer correlate with the digital model.

Weaving of the three segments continued off site until mid-May. The segments were then lowered and disconnected from the guide rails. This process revealed hidden dynamic properties of the weave. While connected to the guide and hoisted, the load distribution causes the weave to almost 'pop' into approximate shape. Once relieved of needing to shed load, the weave becomes flaccid and can flatten dramatically. Temporarily losing shape in this way made the logistics much simpler. Having anticipated the need to further segment the weave to cater for its geometry, the weave could instead be rolled like a textile and loaded onto a flat-bed in

6. Weaving off site. The rail to the right provides both a guide for calibrating the weave density and a rigging member for hoisting the weave. © Phil Ayres, Royal Danish Academy.

7. Installing the ribs and the weave to the ceiling grid at 6m height. © Phil Ayres, Royal Danish Academy.

8. The Shimoni cave segment in its final posture with a 3D print of the Shimoni caves network in the foreground. © Phil Ayres, Royal Danish Academy.

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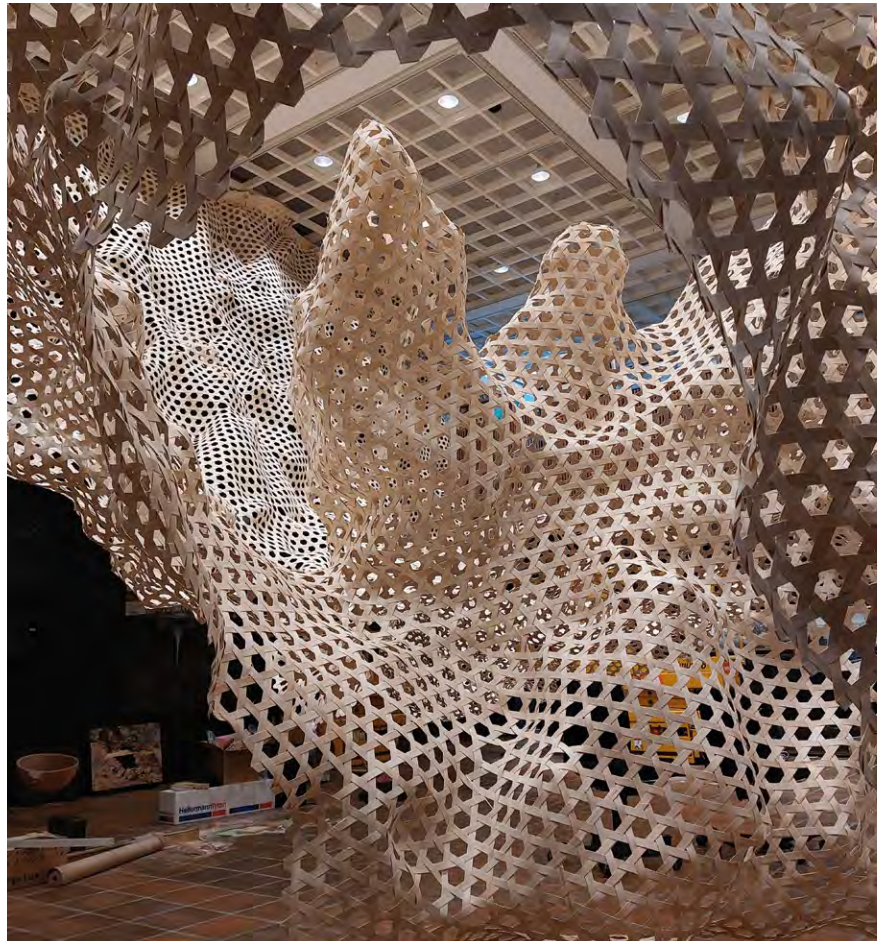

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finished segments. The three segments were individually transported to the museum 8km away. At the museum, a large group of Louisiana staff had been mobilised to carry the segments, each weighing no more than 100kg, into the exhibition space. The weaves were unrolled and showed no local failures in the material. The task of moving the three segments into the exhibition space and laying them out was completed in one morning.

Final assembly

Within Store Sal, multiple hoisting points were attached to the ceiling so that the weave sections could be immediately hoisted into their final position. A ribbing strategy had been developed and prefabricated to connect the weave and resolve its shifting angle of posture as it interfaced with the receiving walls and ceiling. The ribs supported two layers of thin bent ply to continuously sandwich the weave. Scissor lifts provided access to the 6m-high ceiling grid, allowing the ribs to be mounted in short discrete sections (Fig. 7). With the edges in place and the three segmented sections woven together in-situ, the cave took up its final geometry. All hoisting points were removed, leaving the cave to hang unassisted (Figs. 8, 9). In one area of vertically extending features, secondary weavers were introduced to double the thickness and provide reinforcement to protect against sagging over the exhibition period (Fig. 10). Application of exhibition lighting activated powerful secondary effects of light and shadow, providing strong cues for inviting visitors into the openings that can extend down to floor level (Fig. 11).

Weaving was completed two days prior to the official opening of the Cave_bureau exhibition on 29 June, 2023. The show closes on 14 January, 2024.

Discussion and outlook

The woven Shimoni cave segment demonstrates how, through the application of computation, the inherent intelligence of Kagome craft can be amplified to realise near-net approximations of complex design targets, at architectural scale, in a rationalised and systematic way, using straight stock, low-impact, and renewable materials that are fully retrievable. Furthermore, the methods developed for the translation from digital topological maps to physical weave support and empower people newly introduced to the Kagome technique, by managing complexity and providing robust checks for topological accuracy. Whereas the Shimoni caves project demonstrates geometric scale and complexity exceeding the quotidian origins of the craft's basket-making origins, it continues to employ like materials with similar mechanical properties.

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9. View of the woven Shimoni cave from the Store Sal gallery. © Kim Hansen, Louisiana Museum of Modern Art.

10. A small cluster of vertical features were woven at double material thickness to ensure their long-term stability. © Phil Ayres, Royal Danish Academy.

11. Exhibition lighting activates space and invites entry from underneath. © Kim Hansen, Louisiana Museum of Modern Art.

A key impediment in the direct transfer of the weaving principles to architectural and structural application is achieving material interlacing with members that have sufficient load-bearing capacity. In the corner of the Cave_bureau exhibition is a wall-mounted prototype weave of six cells with a pentagonal singularity woven from solid, straight stock, beech members with a 60x30mm cross-section. The weave does not require any chemical or mechanical fixings, as it benefits from the inherent jamming that occurs from the network of reciprocal triangles. This prototype indicates where our research is heading, funded under a five-year Semper Ardens Accomplish grant from the Carlsberg Foundation. This work is now emboldened by the validation of our digital tools and workflows through the realisation of the Shimoni example.

Project participants

Cave_bureau: Kabage Karanja, Stella Mutegi
Curators: Kjeld Kjeldsen, Mette Marie Kallehauge
Exhibition architect: Brian Lottenburger
Weave concept and digital development: Phil Ayres, Jack Young
Project management and delivery: Jack Young
Weavers: Sabine Kongsted, Chloe Liang, Sebastian Hedevang, Zander Vind, Johan Reeh, Alexander Ølbye, Lovisa My Loren, Mari Sagedal, Alberte Westergaard, Javier Tapia, Malthe Mohr Johnsen, Jack Young, Phil Ayres.
Material consultancy and supply: Franz Rubach, Miranda Ruback, B.V. INAPO, NL

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DIAMANTI
3D-PRINTED, POST-TENSIONED CONCRETE CANOPY

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UNIVERSITY OF PENNSYLVANIA - POLYHEDRAL STRUCTURES LAB (PSL)
MATHIAS BERNHARD
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE (EPFL)
DAMON (MOHAMMAD) BOLHASSANI / FAHIMEH YAVARTANOO / JAVIER TAPIA
THE CITY COLLEGE OF NEW YORK (CCNY)
KAROLINA PAJAK / MYLÈNE BERNARD / LEON TROUSSET
SIKA CORPORATION
PAUL KASSABIAN / BLAISE WALIGUN
SIMPSON GUMPERTZ & HEGER (SGH)

This academia–industry collaborative project, *Diamanti canopy*, demonstrates the design and fabrication of a combined compression and tension funicular canopy with periodic anticlastic, diamond surfaces (Fig. 3).
The canopy is a part of the European Cultural Centre's 2024 biennial exhibition, 'Personal Structures', in Venice, Italy, at the Giardini della Marinaressa (Fig. 2). Utilising both 3D concrete printing (3DCP) and post-tensioning technologies, the canopy spans 10m and is supported by a cross-laminated timber (CLT) platform (Fig. 4).
The structural form of this composite canopy directly considers both compressive and tensile forces, inherently developed in concrete structural systems, by distributing loads through its unique, minimal-mass geometry.
The CLT platform suggests how the combination of a carbon-negative material and concrete can be used in contrast to common construction methods where concrete is typically used as the load-bearing support and wood as the spanning element. Hence, the lightweight design of the *Diamanti canopy*, spanning over and supported by the CLT platform, showcases the innovative use of these materials, while also satisfying the Venice Port Authority's installation requirements.

The historical design of ancient masonry structures continues to inspire the use of compression-dominant structures in the Architectural, Engineering, and Construction (AEC) sector because of their ability to perform well and minimise the amount of material, mass, and embodied energy required (López López *et al.*, 2014, and Nuh *et al.*, 2022). While beneficially reducing the overall quantity of material needed for construction, such systems call for extensive external provisions to maintain compression-only load paths requiring, for example, either fixed boundary conditions or the inclusion of horizontal tension-ties as constraints. Other safety requirements may necessitate the inclusion of additional reinforcement, such as steel fibres, to enhance performance, but can limit the structure's ability to be recycled.

The exhibited canopy goes beyond compression only by embracing tension as an unavoidable force in systems resilient to different loading scenarios. Hence, a combined form-finding and fabrication approach was developed to achieve the innovative structure with the intention of also minimising carbon through reduced materials and recyclability. Through the design freedom enabled by the design approach, 3DCP, and the use of post-tensioning, the final design favourably has minimal reinforcement

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while achieving the desired structural performance. Overall, the *Diamanti canopy* demonstrates how, through the combination of modern technologies and the development of a non-restrictive, comprehensive design approach, new structural forms can be achieved that lead to enhanced sustainable practices.

The geometry-based structural design method of polyhedral graphic statics (PGS) (Akbarzadeh, 2016; Lee, 2018) provided the design freedom to achieve a structure that is capable of dealing with developed compression and tension forces. Polyhedral cells, defined from the resulting structural form, were used to contort periodic anticlastic surfaces, specifically the diamond triply periodic minimal surface (TPMS) geometry to align with the principal stress directions. The diamond TPMS unit's geometry enhances the structural form's geometric stiffness and inherently provides the internal conduits for the post-tensioned cables, resulting in a fully integrated material-structural system.

The use of 3D concrete printing allowed for the effective realisation of the innovative structural form, which otherwise could not be achieved using standard construction techniques. Prefabrication optimisation and construction schemes were developed to address additive manufacturing constraints. To optimise for printability, signed distance function (SDF) (Bernhard *et al.*, 2018; Blinn, 1982; Bernard *et al.*, 2021) combined the funicular form and the TPMS geometry into a smooth, unified model. To print the 10m canopy, the design was divided

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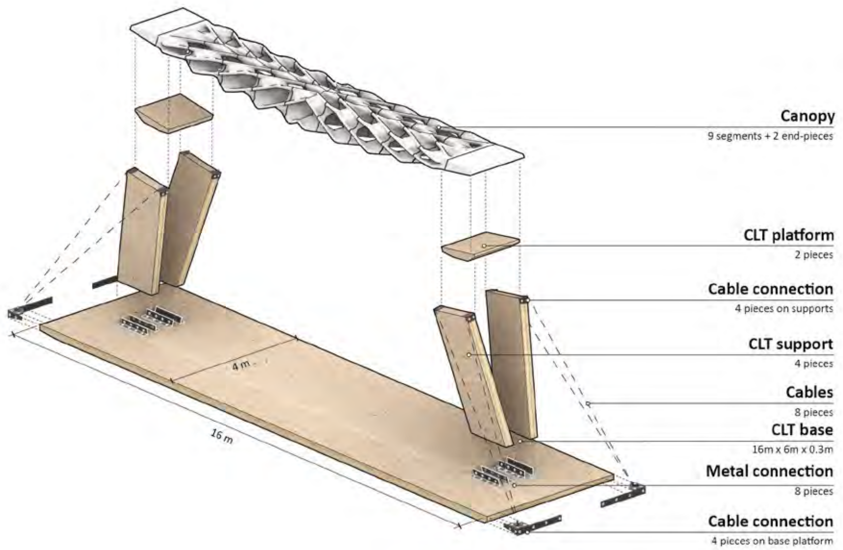

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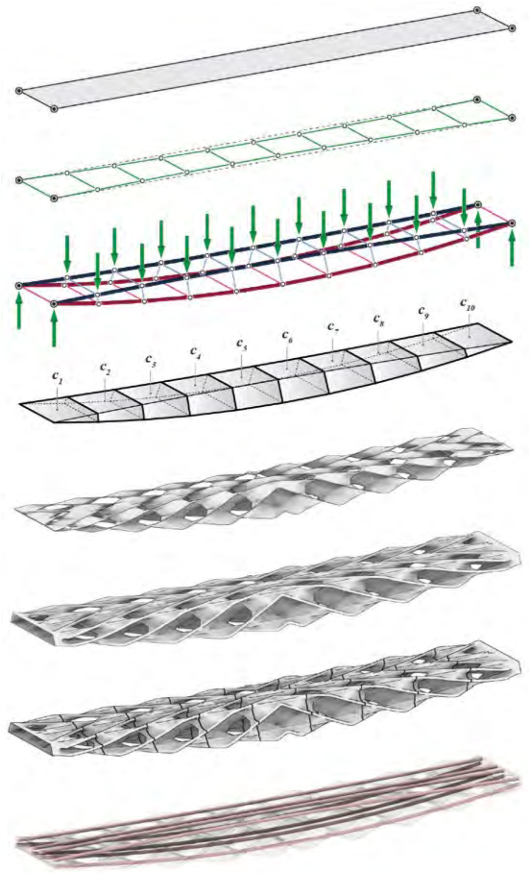
1. 1:10-scale clay model fabricated using the in-house modular printer. © Polyhedral Structures Lab, University of Pennsylvania.

2. Rendering of canopy at the Giardini della Marinaressa, Venice, Italy: © Polyhedral Structures Lab, University of Pennsylvania.

3. 3D concrete printed periodic anticlastic funicular canopy. © Polyhedral Structures Lab, University of Pennsylvania.

4. Assembly concept of canopy exhibition. © Polyhedral Structures Lab, University of Pennsylvania.

5. Structural form-finding through polyhedral graphic statics and volumetric modelling. © Polyhedral Structures Lab, University of Pennsylvania.



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into segments that ensured preferred structural behaviour and optimisation algorithms were developed to effectively slice the segmented geometry with non-parallel planes perpendicular to the direction of compression force flow. Additional computational algorithms were developed for efficient non-continuous printing to minimise the material dripping and to avoid collision, since the geometry of the segments includes multiple disconnected loops.

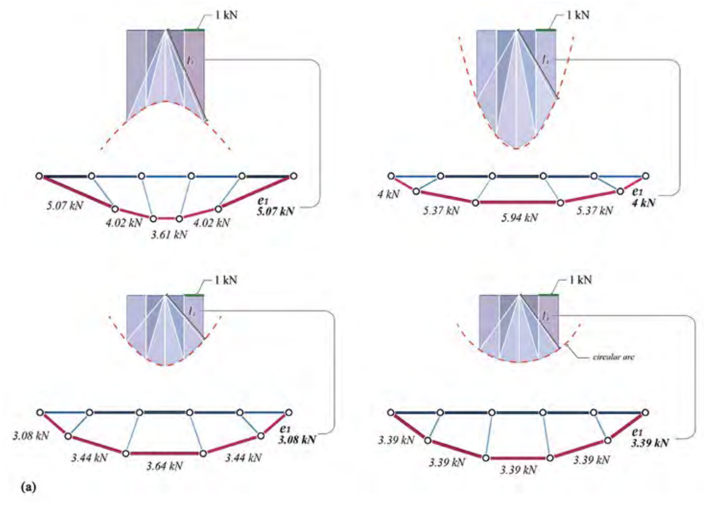
The overall design and fabrication approach in this work includes multiple intertwined innovative strategies that result in an extremely efficient structural system utilising 3D concrete printing and post-tensioning that reduces the construction materials needed compared with conventional structural systems. The prefabrication strategy yields faster erection times, reduces soft construction costs, eliminates the need for formwork, allows for recyclability, and minimises the overall carbon emissions of concrete construction.

Design

A comprehensive computational methodology for form-finding, optimisation, and digital fabrication was developed to design the canopy. The method begins with the generation of a geometric design using PGS, succeeded by the utilisation of volumetric modelling (VM) for structural materialisation. With respect to fabrication, details concerning 3DCP were considered through the development of print-specific optimisation algorithms. The entire computational method for the canopy is illustrated as a workflow in Fig. 5. While applied here to the canopy, this computational method is general in that the process from design generation to digital fabrication preparation can be employed for a wide range of applications. The specifics of the method are discussed subsequently.

Structural form-finding through polyhedral graphic statics

The structural form-finding process begins with the implementation of graphic statics. Conventional two-dimensional graphic statics establish a reciprocal relationship between form and force. This reciprocity principle allows for the considered forces and form to be altered without violating structural equilibrium, providing design freedom. With stability guaranteed, a range of stable structural forms can be generated considering both tension and compression forces (Fig. 6a). To effectively manage design requirements and material properties for the concrete canopy design, it is beneficial to maintain constant tension forces. In the context of 3D printing,



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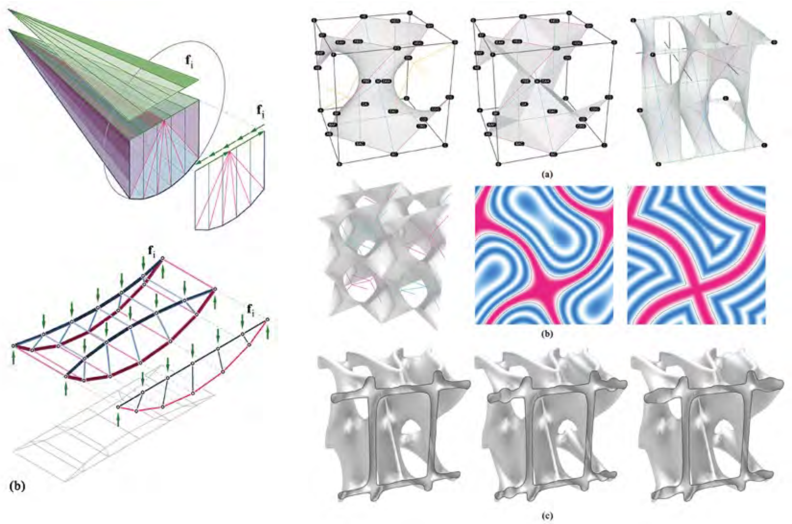

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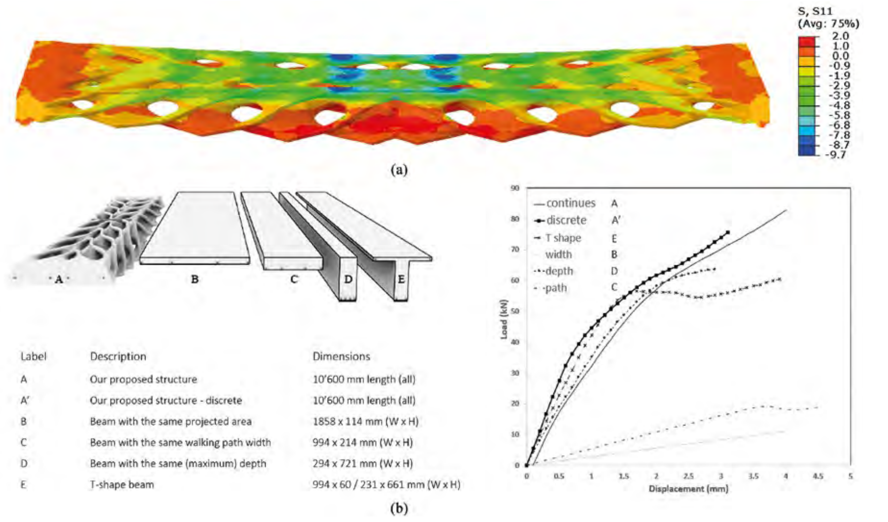

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concrete materials exhibit anisotropic behaviour, meaning their properties vary depending on the direction of the applied load. The final constant tension force determined from graphic statics can be used as the post-tensioning force for the cables that run through the canopy to ideally produce constant compression. While the constant compression force intended to be developed from post-tensioning the system reduces the risk of localised stress concentrations and delamination of printed layers, the steel post-tensioning strands provide necessary steel reinforcement, allowing for the canopy to deal with tension forces that could be developed from other loading scenarios.

After using two-dimensional graphic statics to determine a geometry capable of dealing with combined tension and compression forces, PGS is utilised to extend the form and force in the third dimension (Fig. 6b). For this project, all the edges defining the two-dimensional force diagram are extruded to two points to establish a new three-dimensional force diagram. The same strategy used in two-dimensional graphic statics to ensure constant tension forces is also applied here. With the form established, segmented cells are defined to be used later for materialisation and VM of the anticlastic surfaces.

Embedding periodic anticlastic surfaces

Since first described by Hermann Amandus Schwarz (1865), and later by Edvard Rudolf Neovius, Alan Hugh Schoen, and others, periodic anticlastic surfaces, specifically TPMS, are studied in several domains, including mathematics, physics, material science, engineering, and architecture to name a few.

A surface is defined as anticlastic when the centres of curvatures are located on opposing sides, forming a hyperbolic paraboloid. The intricate structure of periodic anticlastic surfaces, their high surface-to-volume ratio, and their property of separating space into two interwoven but disconnected sub-spaces, make them promising candidates for a variety of applications, including, for example, medical implants, lightweight infill structures, and heat exchangers. While the gyroid surface, discovered by Schoen, is commonly the focus of various applications, the Schwarz-D TPMS, also named 'Diamond' by Schoen, is implemented here for the canopy's design because of its diamond cubic labyrinths. The diamond surface can be approximated by the implicit function:

$$\cos x \cos y \cos z - \sin x \sin y \sin z = 0$$

The surface is the 0-level isosurface of this function, separating space in a positive and a negative half-space. Unlike the gyroid, the diamond has several straight lines embedded in its surface that can be separated into three sets (Fig. 7a). A series of transformations are applied to rotate, translate, scale, and mirror the initial unit characteristics to align with the geometry generated through PGS. While different alignments can be explored, the continuity of the smooth surface must be guaranteed by enforcing the wavelength to be an integer multiple of 1 when cells are lined up and morphed into the form diagram, as done with the canopy illustrated in Fig. 5.

While the smooth zero mean curvature of minimal surfaces is beneficial in some applications, it poses some interesting challenges when 3D printed in concrete. The shallow horizontal parts of the surface at the saddle

6. Force and form diagrams of the geometry generated using a) graphic statics, and b) polyhedral graphic statics. © Polyhedral Structures Lab, University of Pennsylvania.

7. Periodic anticlastic surface and volume generation: a) diamond unit cell and approximated polyhedral surface; b) rhombi structures revealed by red and blue labyrinths; and c) thickened diamond surfaces with blended cavities. © École Polytechnique Fédérale de Lausanne.

8. Finite element modelling and analysis, and comparison with other beam structures. © City College of New York.

points constitute large overhangs that lead to printing in mid-air or can lead to structural collapse. To overcome this challenge, the implicit surface was replaced by a topologically identical polyhedral version (Fig. 7a), which natively contains angles acute enough to be readily printed. This polyhedral simplification (Fig. 7a) embraces the stunning relation between the labyrinths (Akbari *et al.*, 2021), Laves graphs, and VM with distance functions, whereby the diamond surface is equally distant from both labyrinths (i.e., continuous interwoven Voronoi cells), and appears to be made of planar rhombi (Fig. 7b).

Volumetric modelling

The 0-level isosurface of an implicit function – for example, an SDF – delimits the positive from the negative subspace: everything negative is considered inside the object, and everything positive outside. To materialise the surface itself, the object needs to be defined with an 'inside' and 'outside'. A straightforward way to achieve this is by creating a shell SDF in the form, where *v* is the original distance value and *d* is the desired thickness of the shell. This strategy works well for exact distance functions that exist for many primitives (Bernhard *et al.*, 2018). However, since TPMS are approximated using trigonometric functions, their return values do not reflect actual correct metric distances (Fig. 7b). Applying the shell function does not result in a constant thickness offset of the original surface. The cells in the form diagram vary significantly in size and the same value for *d* would result in very different thicknesses of the shell along the canopy. Additionally, 3DCP requires the contour to be equally spaced – if the surfaces are too close then the extruded material overlaps and collides, diminishing the visual quality; if too far apart, the material does not bond, thereby diminishing the structural integrity. Therefore, a multi-step translation is applied between volumetric and mesh modelling. The polyhedral simplified unit cell single surface is deformed, preserving its topology such that it aligns the unit cube with the hexahedral cells of the form diagram (Fig. 5, step 5). The mesh for each quadrant of the canopy is converted into a distance field to allow for an exact offset (Fig .7b).

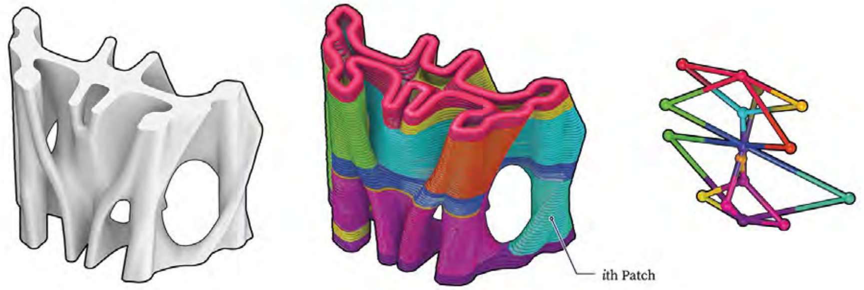
The straight lines embedded in the surface align and are perpendicular with the main canopy's thrust lines – that is, the locations where tension and compression forces develop (Fig. 7a). This embedment allows a direct transfer of compression forces without buckling the doubly curved surface. Since the canopy will experience tensile forces in its lower regions, cavities for post-tensioning steel cables are integrated in the canopy's final design by locally dilating the opposite contours (print paths) of the initial shell. Capsules are created along each cable segment and united with the shell (Fig. 7c). With conventional boundary representation modelling, both thickening the mesh by a constant offset and the union of it with more objects would be prone to failure. Beneficially with VM, shapes are computed rather than constructed and the Boolean union computations are effortless. While a strict union leads to hard edges where the objects intersect, both slowing down the printing and being aesthetically displeasing, a smooth union is performed based on exponential functions (Bernhard *et al.*, 2018), which instead seamlessly blends the cylinders into the shell (Fig. 7c).

Numerical and experimental analysis

To understand the structural performance of the canopy, a finite element model was developed and analysed (Fig. 8a). Considering different loads, such as self-weight and service loads, the finite element analyses indicate that the canopy's displacement is significantly less than the maximum displacement limit established by the American Association of State Highway and Transportation Officials (AASHTO, 2008) design guidelines for spanning structures. A further study was conducted to understand the overall efficiency of the canopy compared with other common structural components that span similar distances. While the canopy initially shows a 14% strength reduction compared with the T-shape beam, by increasing the displacement, all the beams experience plastic deformation, while the canopy favourably shows elastic behaviour. The performance of the canopy compared with other common structural components with the same boundary conditions, the position of reinforcement, the volume of concrete, and an applied displacement on the mid-span, are shown in Fig. 8b. To validate the numerical analyses, several physical models and experimental programs were developed to investigate the structural performance of the canopy. Scaled and full-scale canopies were printed, and their structural performance studied using physical load tests to characterise the properties of the 3D-printed concrete post-tensioned parts and match the analytical results of the finite element analysis with the observed behaviour. These tests led to the development of post-tensioning strategies and techniques to further minimise needed reinforcement and ensure recyclability.

Fabrication

To actualise the designed canopy, both 3D concrete printing and post-tensioning technologies were utilised. Unlike traditional concrete structures, no formwork is needed for the canopy and, indeed, could not be used because of the complexity of the canopy's form. Hence, a multi-component, accelerated 3D concrete printing system was used to print the canopy. The canopy was divided into nine segments, since, at 12m, it would not be feasible to print the canopy all at once. The segments are combined by threading steel cables, 'tying' all segments together, and then compressed when post-tensioned. The assembled canopy is elevated and placed on CLT columns attached to a base for display. The display setup (Fig. 4) was devised with consideration of the soil profile of the Giardini della Marinaressa in Venice and to best exhibit the canopy.



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To ensure successful print and assembly, models of the canopy at four different scales, 1:10, 3:10, 1:2 (Fig. 10), and 1:1, were produced. The 1:10 scale model was printed to understand the nuances of the canopy's structural form using an in-house-developed desktop 3-axis clay printer, featuring a modularised compressive hopper and an auger-embedded extruder, and assembled by post-tensioning steel strands (Fig. 1). The assembly process of the 1:10 scale model was conducted using an upside assembly procedure. As a high-fidelity proof-of-concept, 3m, half-scaled, and full-scaled versions of the canopy were printed using the multi-component, accelerated 3D concrete printing system, to best understand the printing process and the feasibility of assembly (Fig. 12). Overall, this prototyping informed needed printing procedures and assembly schemes on how to best digitally and physically fabricate and construct the full-scale canopy.

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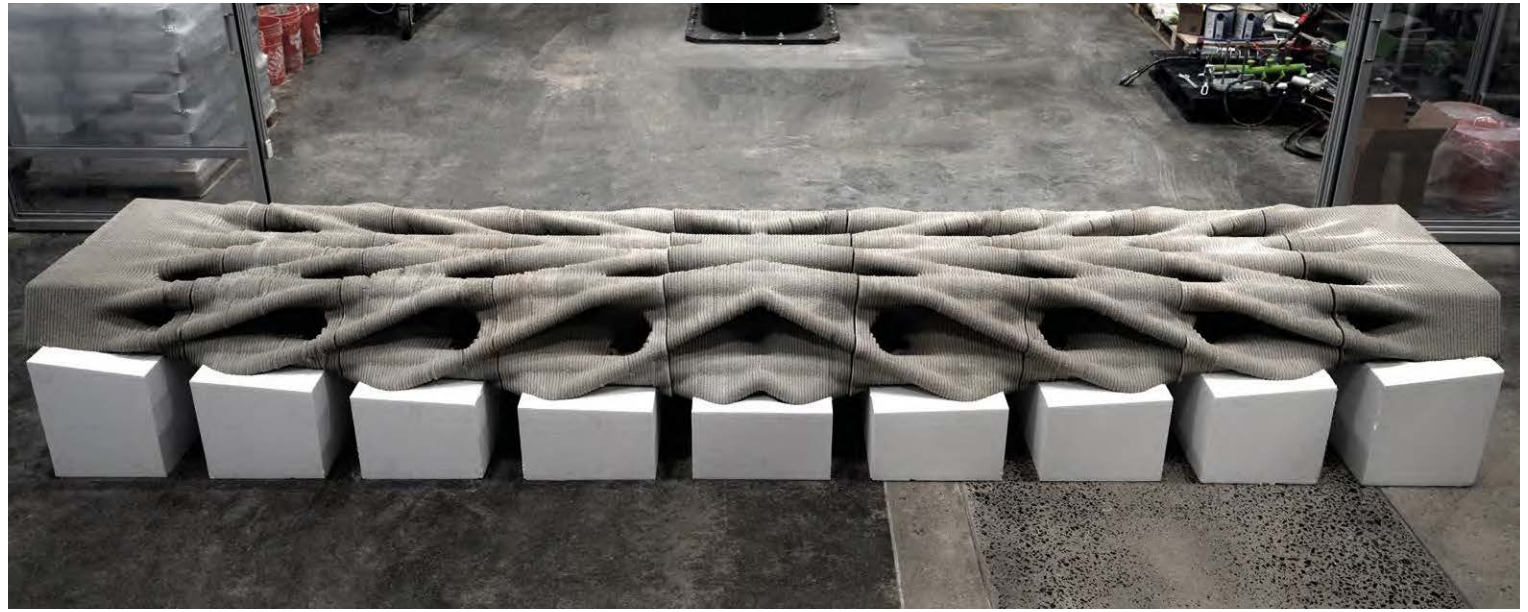

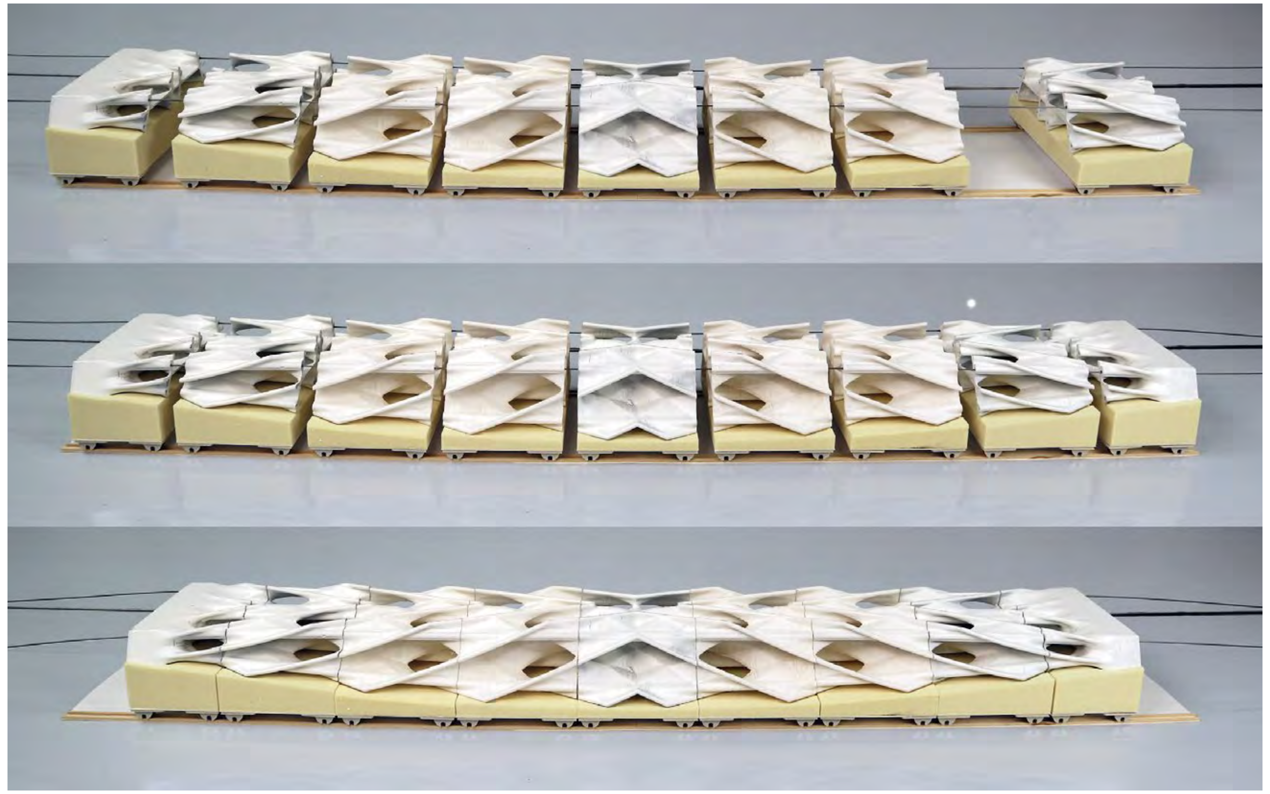

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9. Continuous toolpath patches generated utilising a dependency graph. © Polyhedral Structures Lab, University of Pennsylvania.

10. 1:2 scale (5m) 3D concrete printed canopy. © Polyhedral Structures Lab, University of Pennsylvania.

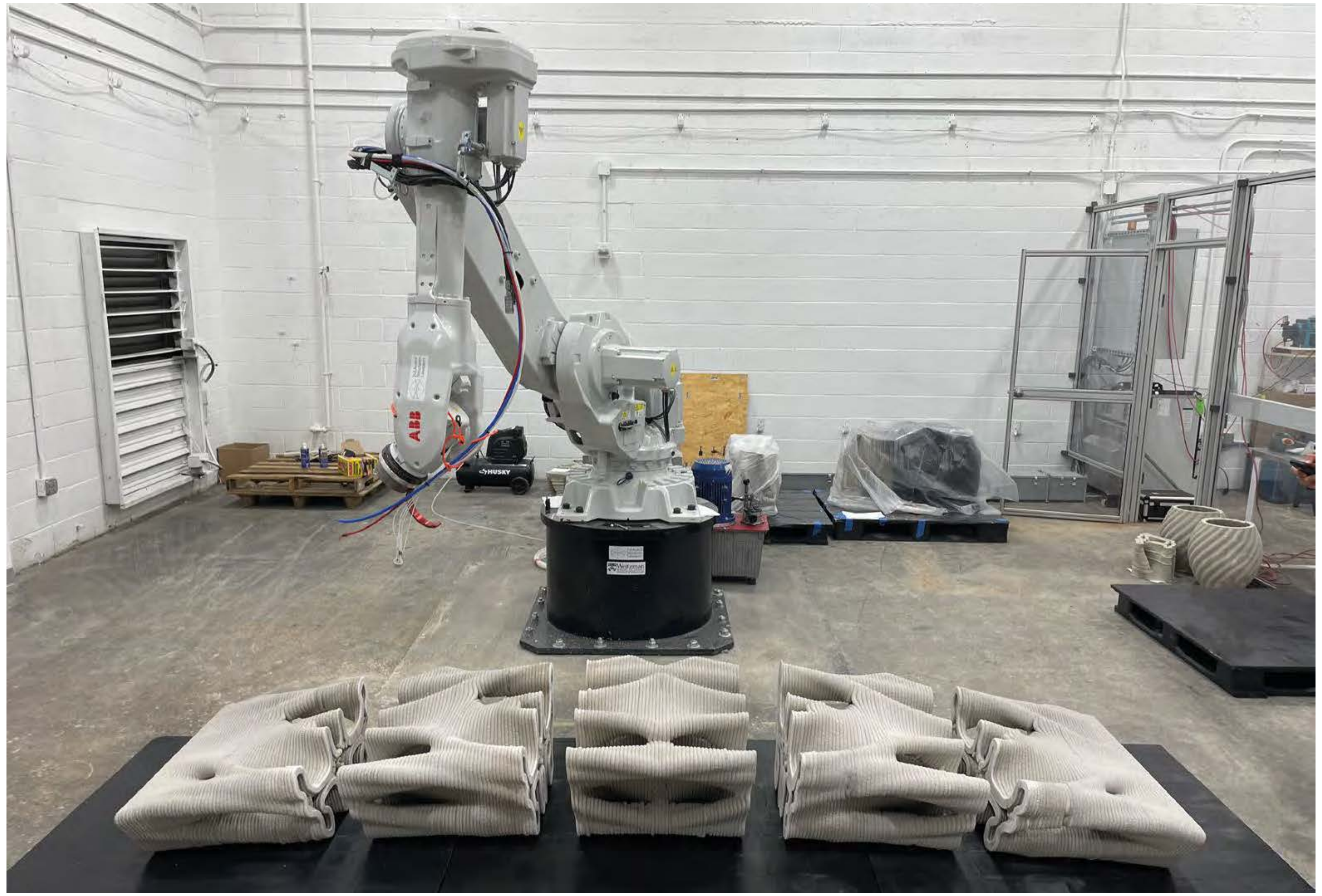
11. Machined foam, caster, rail system for assembly and post-tensioning. © Polyhedral Structures Lab, University of Pennsylvania.

Slicing and toolpath generation

Due to the complexity of the canopy's design and the limitations of the large-scale 3D concrete printer, the slicing and final toolpath were adapted to fit this specific process. Non-parallel slicing was used to get the layers perpendicular to the direction of compression forces, brought about by self-weight, during printing. To 3D print non-parallel layers, the printing parameters were adapted to keep the layer width constant. Because of the different inclinations of the layers, the resulting layer heights vary throughout the layer around an average value set to 10mm. Varying layer heights combined with a constant printing speed and extrusion rate create variations in the layer width, around an average set to 30mm. To avoid these layer width variations, an adaptation of the printing speed was implemented based on an algorithm that determines the specific layer height on each point of the toolpath. In case the layer height is lower than 10mm, the printing speed is proportionally increased within the GCode (printing code) to compensate for the layer height variation and keep the layer width of 30mm, and vice versa.

One of the limitations when 3D printing is overhang – that is, parts of the print that slope outwards without support. When the overhang is too high, either the contact surface between the layers is too low to enable further layers to be deposited on top, or the material does not support the structure's self-weight before setting, and parts of the print collapse. Overhangs can be detected during the slicing process by extracting the normal vectors to the mesh model on each face, enabling easier refinement of the shape without creating waste through physical 3D-printing trials. Overall, a goal of reducing overhangs below 35° to maximise the success rate of the print was set.

In addition, since the canopy has hollow sections, it could not be printed in one continuous path. Hence, a few layers were printed at once, and then a 'jump' was made to print the next group of layers. To avoid material dripping during jumps, the material extrusion was halted; however, prolonged stops can potentially lead to the printer nozzle clogging. To reduce the risk of clogs, which are more likely to occur if the extrusion is stopped for more than 2.5 seconds, the printing path was optimised to ensure jumps would occur outside of the printing area, preventing the dripping of excess material on the 3D-printed element. The convex hull of the toolpath was generated to obtain the contour curve of the element; then, for each jump, the contour was duplicated and moved to the respective



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height of the jump. Finally, the contour was split at its closest point with the end of the current layer grouping and the start of the next layer of group. A connecting path linking those points to the split contour was created, giving one final path for each jump that can then be connected to the layers. For jumps with a duration of less than 2.5 seconds, a simple arc-shaped path was deemed sufficient. This optimisation, shown in Fig. 9, reduced potential printing issues and improved the quality and aesthetics of the part.

3D concrete printing and assembly

There are different technologies for 3D concrete printing available on the market, but the complexity of the canopy's design and the toolpathing needed indicated that a multi-component, accelerated system should be chosen for this project. The mix design incorporates three components, and follows this process: mortar powder is mixed with plasticiser and water in a continuous mixer, and then it is pumped to a high shear rate mixing printhead mounted on a robotic arm. At the printhead the mix is accelerated and extruded through the nozzle. The accelerator allows for a fast concrete setting time and higher overhang values. In comparison to one-component systems, where the height of the print is bound with a slower setting time of the layers that must withstand the load of the subsequent layers, an accelerated system allows for taller prints in one session with overall thinner walls. Nevertheless, the use of an accelerator with the concrete mix can influence its interlayer bonding strength. However, this issue has been accounted for in the canopy's design and through trial printing.

12. 3m concrete print of the canopy. © Polyhedral Structures Lab, University of Pennsylvania.

Another important aspect of 3D concrete printing is testing the material properties and using correct values for the finite element calculations. For regular cementitious systems, material properties such as compressive strength and flexural strength are measured using cast elements according to precise standards and methods. Unlike in regular cementitious systems, a widely accepted standard for 3D-printing applications does not exist, and while the mechanical properties of the concrete-mortar itself can also be measured on cast elements, it is already known that the presence of layers will affect their actual mechanical properties. Therefore, during the evaluation of the project, several adaptations of existing standards were made to best measure the influence of printed layers on the material properties. Then, the cast concrete properties were compared with the printed properties in different directions of the print to best understand the mechanics and characteristics of the material.

Through full-scale prototype printing, additional adjustments were made to the printing policy and toolpathing, as well as minor alternations to the design, to ensure successful fabrication. Between the prototyping and the larger-scale prints, an assembly strategy was developed. This strategy included how to best move, manipulate, and assemble the individual canopy segments for post-tensioning. An assembly sequence was developed using the small-scale prototype, whereby the canopy segments were placed on machined foam blocks with casters. Using a rail system, the individual pieces were placed together and post-tensioned (Fig. 11). Additional strategies for manipulating and placing the full-scale canopy for exhibition were implemented.

Closing remarks

The design, fabrication, and exhibition of *Diamanti canopy* demonstrates how the combination and development of new and existing methods and technologies can lead to high-performing composite structures with reduced material. The comprehensive computational methodology takes full advantage of the geometric capabilities of 3D concrete printing and directly addresses the unavoidable compression and tension forces developed in concrete structures by using post-tensioning. Overall, this project showcases how these technologies can be used for a more sustainable practice where high-performing structural systems can be produced and material recyclability can be achieved, reducing the overall carbon and embodied energy consumption.
The authors hope that this collaborative project inspires the AEC sector to implement and further develop the comprehensive design and fabrication workflow, thus expanding its use as a mainstream approach for exploring and producing forms that were previously impossible or uneconomical to build with conventional methods.

Acknowledgements

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CO-DESIGN OF NATURAL FIBRE COMPOSITE BUILDING ELEMENTS THE *LIV*MATS PAVILION

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Aims and objectives

With the global population rising and more than half of the world's inhabitants living in urban areas (United Nations Publications, 2019), the surging demand for building stock cannot be met given the construction sector's present rate of productivity. The building sector is responsible for the production of 30% of greenhouse gases worldwide. This calls for comprehensive innovation and a serious commitment to striving for new and efficient sustainable modes of construction.

Fibre composites in combination with computational design and robotic manufacturing offer promising solutions, delivering lightweight, high-performance, and material-efficient structures. However, they typically rely on petrochemical materials such as carbon fibres and epoxy resins depending on non-renewable material sources, which compromise the sustainability of the resulting elements.

This research presents a shift towards natural material systems, using flax fibres in coreless filament winding (CFW). CFW is an additive manufacturing method building up on industrial filament winding while reducing formwork to an absolute minimum. It relies solely on boundary frames to position resin-impregnated fibres placed by industrial robots, allowing for near-full automation (Bodea *et al.*, 2021). The use of natural fibre adds further challenges to the process as a result of the raw materials' imperfections and the associated variability of mechanical properties (Yan *et al.*, 2014). Computational design methods, robotic fabrication equipment, and processes therefore need to be adapted to accommodate these complications.

The approach developed is demonstrated with the design, engineering, manufacturing, and construction of a load-bearing natural fibre shell, the *liv*MatS Pavilion. Designed and developed by ICD and ITKE at the University of Stuttgart and produced and assembled by industrial partner FibR GmbH, it is located in the botanical garden of the University of Freiburg, Germany, and serves as a shelter and outdoor lecture space.

Context

Computational co-design of fibrous architecture (Fig. 2) offers a solution to the challenges the construction sector is facing. It integrates design and engineering methods,

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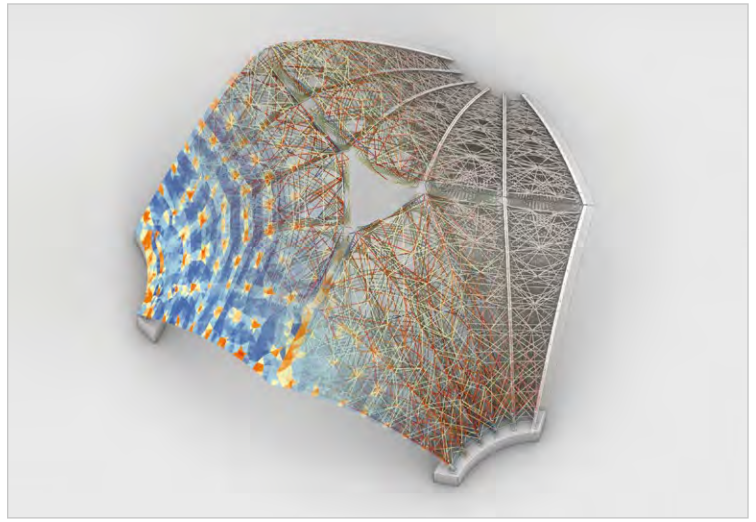
1. Nighttime view of the *liv*MatS Pavilion. © Roland Halbe.



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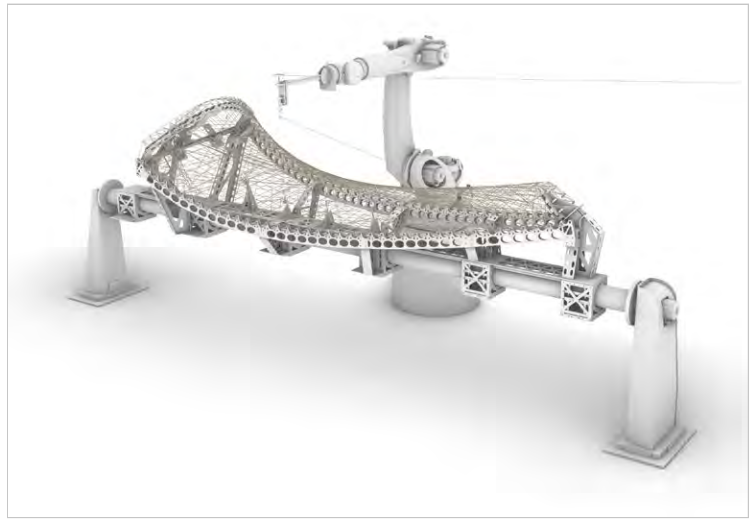

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building and material systems, and fabrication and construction processes (Knippers *et al.*, 2021).

Computation provides urgently required resource effectiveness and material efficiency through customising fibre patterns, and tailoring material deposition based on structural, aesthetic, and fabrication requirements.

CFW is a key enabling technology of fibrous architecture (Prado *et al.*, 2014). It allows for the spatial arrangement of individual fibre strands without elaborate formwork where the shape of the building element is a direct result of the reciprocal interaction of free-spanning fibres between boundary frames (Zechmeister *et al.*, 2020) (Fig. 3). Using this technique, several experimental research examples have been constructed, each investigating specific aspects of the process (Reichert *et al.*, 2014; Dörstelmann *et al.*, 2014; Solly *et al.*, 2019). This foundational research served as a base for the development of large-scale digital fibrous building systems in the recent past (Dambrosio *et al.*, 2019; Dambrosio *et al.*, 2021). However, all these projects relied on the use of oil-based carbon fibres in combination with glass fibres, making their integration in a circular economy difficult.

Flax fibres, instead, are locally available, exhibit short growing cycles of about 100 days, and offer exceptional stiffness and strength compared with other natural fibres (Miao and Finn, 2008) (Fig. 4). Their global warming potential (GWP) and energy intensity are significantly lower compared with carbon fibre (Mindermann *et al.*, 2022b), but their material characteristics, such as less tensile strength and low fibre-matrix bonding related to hydrophilic behaviour (Davies and Bruce, 1998), pose complications that need to be considered in design and robotic fabrication.

Research questions

To account for uncertainties introduced by the variability inherent in the mechanical properties of plant fibres, previously developed methods (Zechmeister *et al.*, 2023a) have to be extended and adapted to consider and emphasise material aspects early in the design process. Calibration and adaptation of production tools and achieved mechanical properties of the composite are reciprocally related, as they depend significantly on the quality and consistency of the fabrication process. Material characterisation thus has to become a driving factor in the design and evaluation process. It further emphasises the need for a cyclical, iterative workflow to successfully integrate natural fibre systems into design and evaluation methods and achieve the required performance. The fundamental research question centres on how to extend and adapt feedback-based design methods to enable material-driven, bottom-up development of composite components and the required configuration and adaptation of fabrication equipment.

Research methods

Integrative, feedback-based design of natural fibre composite components
The load-bearing fibre components are made of spatially arranged flax fibre rovings, which are individually designed according to their required structural performance, the desired aesthetics, and prevalent fabrication constraints (Fig. 5). To negotiate these often

2. Computational Co-design of fibrous architecture. © ICD/ITKE/IntCDC University of Stuttgart.

3. Robotic coreless filament winding. © ICD/ITKE/IntCDC University of Stuttgart.

4. Flax fibre filaments as raw materials. © ICD/ITKE/IntCDC University of Stuttgart.

5. Full-scale component made of spatially arranged flax fibre rovings. © ICD/ITKE/IntCDC University of Stuttgart, Rob Faulkner.

6. Structural testing of full-scale prototype. © ICD/ITKE/IntCDC University of Stuttgart.

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conflicting requirements, an integrative, feedback-based design and evaluation workflow is used to monitor design compliance, structural performance, and fabrication feasibility at all times (Zechmeister *et al.*, 2023b). The structural design is therefore integrated into the workflow following non-standard methods to represent the material system and evaluate its performance (Gil Pérez and Knippers, 2023; Gil Pérez, 2023). These co-design methods are implemented by means of iterative cycles, alternating between design and evaluation, to explore design boundaries, define, develop, and optimise the fibre layup, and verify the safety of the structure by proving its structural integrity. The design evaluation is performed both digitally, by means of simulation, and physically, through prototyping using design models, small-scale specimens to characterise the material, and full-scale production prototypes. Material characterisation acts as an important hub for design decisions and determines the material selection.

Structural simulation is conducted at different levels of detail to simplify the structure at the global scale and investigate the fibre layup at the component scale. Finally, physical evaluation through the testing of prototypes (Fig. 6) is used for the calibration and verification of computational models (Gil Pérez *et al.*, 2022). Computational models act as a data hub for other digital models to serve specialist contractors, fabrication prototyping, and fabrication data protocols for industrial partners.

Material characterisation and evaluation
Material characterisation and evaluation are part of the workflow as dedicated mechanisms to inform computational models, including the variability of mechanical properties in the digital realm. The methods employ a multi-scalar approach; small-scale specimens at an early stage evaluate the material's mechanical performance, as well as its sustainability aspects, and full-scale structural testing (Fig. 6) is used at a later stage to calibrate and validate the results (Gil Pérez *et al.*, 2021). The finite element model of the test setup (Fig. 7) is used as a calibration tool to compare the physical and digital structural performance. The key challenge of using natural fibre materials is the variability and uncertainty related to their mechanical properties, in contrast to synthetic fibres (Yan *et al.*, 2014). This reality emphasises the value of small-scale specimens to provide insights into mechanical performance. In CFW, the comparison of previously used carbon fibre composites with flax fibres, both using oil-based and bio-based resins, was an important step, implemented by star-shaped specimens (Gil Pérez *et al.*, 2019) that reassembled the characteristic

fabrication parameters of a large-scale CFW structure (Fig. 8). The carbon footprint of the materials can be compared based on the strength per mass of material, using the results of the testing. This information provides an initial idea of the embodied energy and GWP of the material and is used to choose the best-performing and most sustainable system. However, the complete life cycle evaluation can only be performed at full scale. Similarly, the final material evaluation should be based on full-scale testing, verifying the structural performance and the possible influences of the difference in scale.

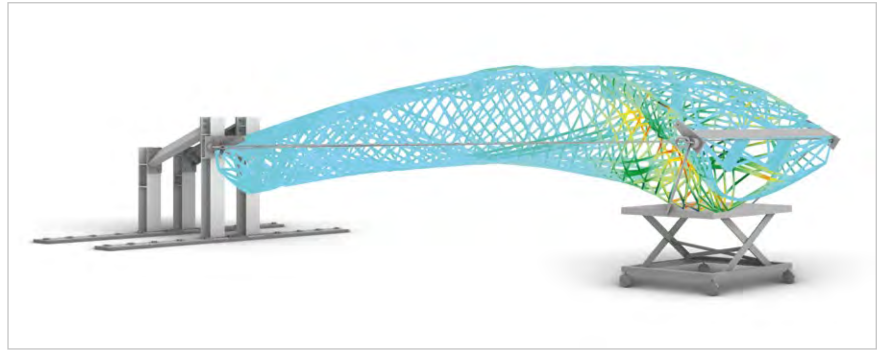
Equipment and process adaptations

Flax fibre rovings are technically assembled products from shorter-grown fibre strands that exhibit the characteristic inhomogeneous and non-standardised behaviour of grown building materials. In particular, the resin impregnation behaviour, and the roving's reduced tensile strength when dry, required significant adjustments to the robotic fabrication process. Material-specific adaptations to the fabrication setup included the adjustment of the fibre impregnation process, material handling and guiding, and an adapted robot code to allow a narrower margin of acceptable fibre-tool alignment angles. The fibre impregnation process was adjusted for a low-friction multi-step impregnation to ensure full and homogeneous saturation of the fibre roving while reducing tension. The tension control mechanism was modified for minimum tension, and all fibre guiding systems had to be friction-optimised in terms of guiding angle and low-friction bearing supports. Most importantly, the machine behaviour had to be adjusted to prioritise a smaller allowable range of tool-to-fibre angles (Fig. 9) during the CFW process over other optional productivity improvement features to avoid the disintegration of the multi-roving bundle.

Research results

Global & component design

The *liv*MatS Pavilion is conceived as an outdoor event space, located in the botanical garden in Freiburg (Fig. 10). It is composed of 15 load-bearing flax fibre components, each one between 4.5 and 5.5m long, radially arranged in three bays of five component types each, and an additional keystone element in the middle to close the shell. It constitutes a genuinely digital building system and demonstrates the design, development, and manufacturing of customised, lightweight, and material-efficient natural fibre building components. The pavilion's radial configuration frames the surrounding botanical garden and blurs the threshold between the fibrous interior and the natural outdoor environment (Fig. 11).



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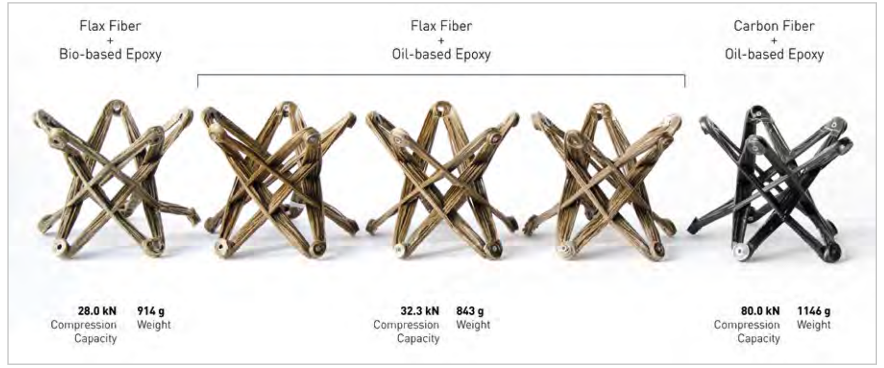

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The load-bearing components are made of spatially arranged flax fibre rovings impregnated with oil-based epoxy resin, individually designed according to their required structural performance, the desired aesthetics, and prevalent fabrication constraints (Fig. 5). Different anchor point configurations were evaluated, leading to a tube-like geometry, which is divided into two parts. The front surface is conceived as a lattice-like fibre layup leveraging the high surface curvature to achieve sufficient interaction between free-spanning fibres. It contains a combination of dense fibre scaffolding with a truss-like longitudinal fibre spine and multiple reinforcement grids to create a stiff surface and reduce the buckling length of the spine. The back part of the component is composed of multiple truss-like layers to add structural depth and transmit wind and snow loads from the roof. It also accommodates support points for the façade to shorten the span of the polycarbonate panels. Each of the components weighs approximately 100kg and can withstand 4 tons in compression, as proven in full-scale structural tests (Fig. 7).

Skin and connection interfaces

To protect the fibre components from water and UV radiation, a polycarbonate skin was developed (Fig. 10). Steel strips along the component's edges provide support for water jet-cut polycarbonate panels measuring up to 6.5m in length and 2m in width. These V-shaped, laser-cut steel arcs had to be single-curved and welded together, connecting to the fibre components using bent steel brackets. Anchor points, located at the edge of the components, as well as on the back surface, act as connection points for the skin. Highly expandable silicone was utilised to seal the joint between adjacent panels. A flat, bonded cover plate safeguards the joint with the opposing panel.

7. Finite element model of the test setup. © ICD/ITKE/IntCDC University of Stuttgart.

8. Comparison of different fibre and resin systems. © ICD/ITKE/IntCDC University of Stuttgart.

9. Optimised tool-to-fibre angle during production. © ICD/ITKE/IntCDC University of Stuttgart, Rob Faulkner.

10. The *liv*MatS Pavilion in the botanical garden in Freiburg. © ICD/ITKE/IntCDC University of Stuttgart, Rob Faulkner.

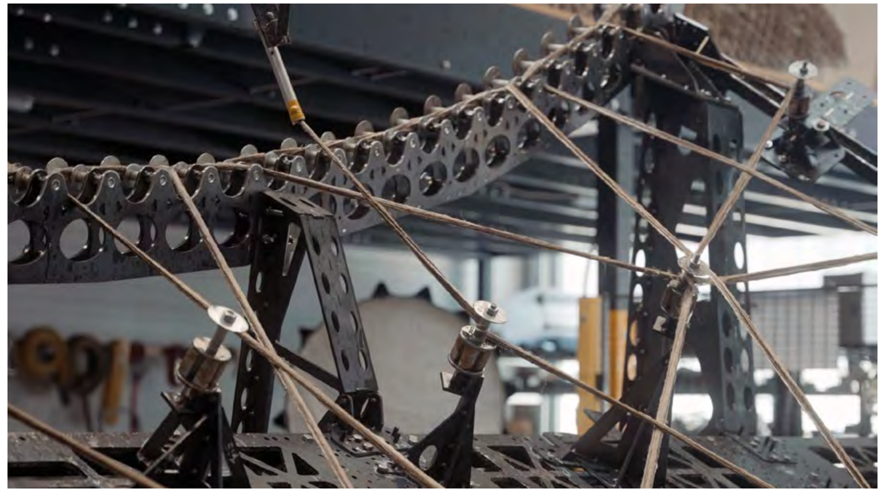
11. Interior view of the *liv*MatS Pavilion. © ICD/ITKE/IntCDC University of Stuttgart, Rob Faulkner.

Keeping the façade panels single-curved while the intersections were vertically above the component margins was a geometric challenge. As a result of the component's single-curved back surface, a straightforward offset was not feasible. Instead, an optimisation approach was employed to recreate the panel edges. The resulting support structure featured several distinctive geometries, which were categorised using k-means clustering, adhering to specified tolerances to minimise both production effort and costs.

Component fabrication and assembly

The early stages of the component design were largely informed by the options and opportunities of various kinematic fabrication setup configurations. For the longitudinal and curved tubular shell segments of the *liv*MatS Pavilion, a robotic fabrication setup with a long horizontal external rotation axis was implemented (Fig. 12) and respectively informed and constrained possible component geometries alongside other parameters such as transport, tempering oven dimensions, handling, and installation.

Several full-scale prototypes were iteratively produced (Figs. 12, 13) to evaluate the impact of the adjusted material system as an integral part of the co-design approach and to reciprocally inform design, and fabrication parameters. The result is a calibration of the various fibre layups in response to a more dynamic geometry emergence throughout the winding process, which could then be anticipated in the component design. The 15 lightweight shell segments plus keystone components were robotically prefabricated, shipped, and installed by the industrial partner. They were easy to handle, showcasing the minimal invasive assembly process of fibrous structures through the use of light tools without noise or dirt emissions. The complexity within the fibrous building components does not affect other construction subsystems. Component-integrated sleeves allow for reversible screw connections between the fibre composite components and provide pre-established screw interfaces for foundation and building skins.



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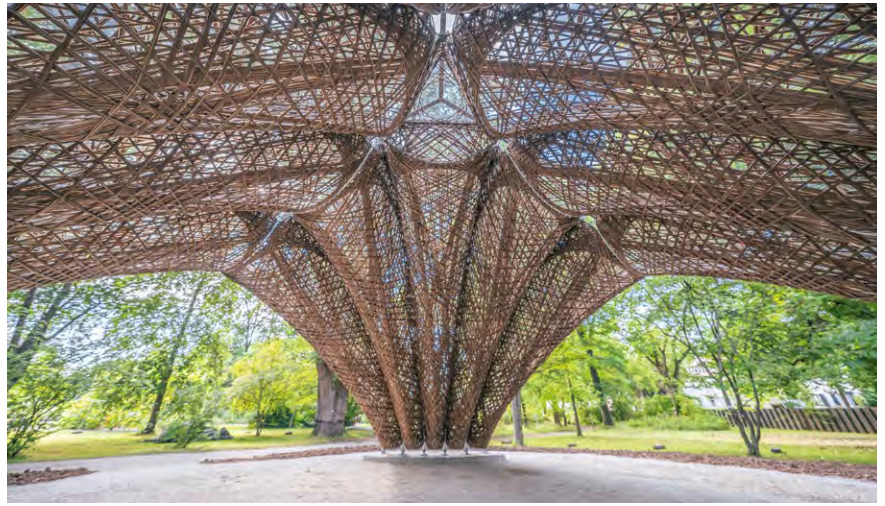

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Conclusion and outlook

CFW enables nearly waste-free and economical prefabrication of lightweight, high-performance building parts. While carbon and glass fibres allow for material-efficient structures, they compromise sustainability and impede their integration into a circular economy. Using plant fibres instead provides eco benefits but adds additional challenges to the design, evaluation, and manufacturing of composite building parts. To accommodate these challenges, co-design provides a flexible conceptual framework for interdisciplinary collaboration and allows for material-driven, bottom-up development, where computation acts as an interface between digital and physical realms. Material system requirements are considered from the outset and material characterisation and evaluation inform the design to account for varying mechanical properties of natural fibre materials.

Life Cycle Assessment (LCA) indicators such as GWP and energy intensity allow for an initial evaluation and comparison of the sustainability of different material systems. Together with material characterisation to determine the composites' actual mechanical properties based on the fabrication equipment configuration used, they provide criteria to select suitable material systems. Integrating comprehensive LCA into design processes is presently under investigation and is considered an important step in assessing design candidates at an early stage.

The fabrication and assembly process of the *liv*MatS Pavilion showed that robotic prefabrication of large-scale flax fibre-reinforced building components requires adjustments in fibre layout, fabrication hardware, and robot control. However, given the proposed adaptations, it does not pose fundamental challenges for its application in CFW. Natural fibres were used in conjunction with petrochemical resins. Partially bio-based resins offer additional gains in sustainability and were tested during the development process but eventually not implemented due to the ambitious project timeline and process-related issues, such as insufficient pot life or unsuitable viscosity, making them difficult to use with CFW. The implementation of fully bio-based resin systems derived from bio-based resources such as plant oils, lignin, or furanyl (Baroncini *et al.*, 2016) will significantly increase sustainability and is currently under investigation. In parallel, further research on suitable additives to the resin system may provide improved properties of the composite, such as an increased glass transition temperature to withstand higher temperatures without losing strength, or flammability retardance to increase the fire resistance of the composite.

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The development of the *liv*MatS Pavilion relies on co-design as an overarching conceptual framework (Gil Pérez *et al.*, 2022). The advantage of this framework is the possibility to incorporate multiple disciplines, allowing the collection of interdisciplinary data during the design process. Advanced monitoring systems can provide insight into the structural behaviour without destructive testing (Mindermann *et al.*, 2022a), and gathering data during the fabrication process can make manufacturing more predictable (Gil Pérez *et al.*, 2023). Besides, co-design is not limited to CFW and can be used for different building and material systems . Implemented through feedback-based computational design, it could also be used in conventional design practice to facilitate decision-making in early design stages and more deeply integrate interdisciplinary collaborators, blurring the lines between design and engineering and making evaluation an integral part of the design process.

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12. Robotic fabrication setup of the *liv*MatS Pavilion. © ICD/ITKE/IntCDC University of Stuttgart, Rob Faulkner.

13. Robotic fabrication of the component´s back surface. © ICD/ITKE/IntCDC University of Stuttgart, Rob Faulkner.

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- **Ben Bridgens** is Professor of Regenerative Architecture in the School of Architecture, Planning a Landscape at Newcastle University, UK, and a founding member of the Hub for Biotechnology in the Built Environment. Bridgens works at the interface of engineering, architecture, and design, critically examining 'sustainable' technologies and exploring the potential for combining traditional construction practices with biotechnology and natural systems to go beyond sustainability and create a regenerative built environment.
- **David Briels** has been a research associate at the Chair of Building Technology and Climate Responsive Design at the Technical University of Munich (TUM) since 2018. In his doctoral research since 2020, he has focused on the integration of passive and active functions in additively manufactured (AM) construction elements, using performance-based parametric design. In particular, he is investigating thermal insulation performance and thermal load-shifting potential in monolithic AM wall elements.
- **Xan Browne** is an architect and researcher with a focus on load-bearing structures, (waste) timber, and novel modes of resource flow. His work is situated in close connection to practice, evolving through growing collaboration with industry. Motivated by contemporary issues such as the limitations of biomass availability and the need to develop new types of timber structures, his research continues to investigate how localised construction ecologies can contribute to efficient timber buildings through closer relationships between material availability, design, production, and inhabitation.
- **Dr Coralie Brumaud** is a senior materials scienctist with a civil engineering and architecture background. Her PhD at Laboratoire Central des Ponts et Chaussées (now University Gustave Eiffel) focused on the influence of bio-based polymers on cementitious materials. She has sonce worked at Saint-Gobain Research, in charge of projects dealing with formulation and rheological optimisation of mineral products. Since 2014, she has worked at the Chair for Sustainable Construction at ETH Zürich and is presently responsible for research on alternative and regenerative building materials.
- **Theo Bürgin** is a construction professional with a comprehensive background in innovative construction. Possessing degrees in construction, he specialises in implementing cutting-edge construction technologies, demonstrating a steadfast commitment to advancing sustainable construction practices. Notable achievements include contributions to the Incidental Space at the 2016 Biennale Venezia, the Smart Slab at the Dfab House and the HiLo Roof at Nest/Empa, and the Striatus Bridge at the 2021 Biennale Venezia.
- **Mark Burry** is the foundation director of Swinburne University of Technology's Smart Cities Research Institute. He was previously the Professor of Innovation and Director of the Spatial Information Architecture Laboratory and founding director of the Design Research Institute at RMIT University, Melbourne, Australia. He is also executive architect and researcher at the Sagrada Familia basilica in Catalonia, Spain. Burry has been a visiting professor at the University of Liverpool, MIT, the Universitat Politècnica de Catalunya, and Victoria University of Wellington. He has collaborated with Gehry Partners LLP, dECOi Paris, Foster and Partners and Arup.
- **Edouard Cabay** is programme head and senior faculty at the Institute for Advanced Architecture of Catalonia, where he co-directs 3dPA, a programme that focuses on developing new housing solutions with 3D printed earth, enabling non-standard building solutions with fully recyclable materials that require minimum energy. This groundbreaking project has been awarded the New European Bauhaus prize as well as having been exhibited at the last two editions of the Venice Biennale of architecture.
- **Elisabetta Carnevale** is director of ADT Earth Architecture, an earth construction consultant and an architect. She is a post-graduate DSA in Earth Architecture from CRAterre (International Centre for Earth Architecture), and ENSA Grenoble. As an expert in earthen architecture, she has been working on the Diriyah giga project and on Al-Ula earthen heritage in Saudi Arabia, as well as on the conservation of UNESCO earthen heritage in Cuenca, Ecuador. She lecturers at the Institute of Advanced Architecture of Catalonia (IAAC), and at La Salle Barcelona.
- **Dr Oriol Carrasco** is a senior fabrication expert at the Institute for Advanced Architecture of Catalonia (IAAC), with extensive expertise in composite manufacturing. Carrasco teaches in the MAA and 3dPA programmes and is co-leader of the Design with Nature research stream, teaching in the metabolic introductory studio. Since 2005, he has combined teaching with working in the engineering and architectural fields, collaborating with key firms to develop projects in Europe and South America.
- **Gianluca Casalnuovo** is a research associate at the Institute for Design of Structures (dos) at the Karlsruhe Institute of Technology (KIT). He is a structural engineer and graduate architect and in his previous experience was a computational designer at the design consulting company Arup Italy. His research interests are geometric optimisation, new material systems, fibre composite structures, and generative algorithms in architecture.
- **Kunaljit Chadha** is an architect with expertise in large-scale digital and robotic manufacturing. His research focuses on synthesising non-standard material with digitally native fabrication techniques for architectural construction. Between 2016-21, he contributed to various academic programmes and funded research projects within the Advanced Architecture Group at IAAC, primarily focusing on developing new robotic processes for digital fabrication. Kunal is presently a PhD researcher at Gramazio Kohler Research ETH.
- **Hua Chai** is a PhD researcher at the University of Pennsylvania's Weitzman School of Design, in the Polyhedral Structures Laboratory (PSL). His research is characterised by blending computational design with structural engineering across various scales, from the intricate micro-level to the comprehensive building level. The focus is centred on integrating advanced form-finding processes with novel materialisation strategies, aiming to develop efficient and optimised structures.
- **Eduardo Chamorro Martin** is an architect and researcher with a focus on additive manufacturing, digital fabrication, materials, robotics, and emerging technologies. He is currently a PhD candidate at Swinburne University of Technology and the Institute for Advanced Architecture of Catalonia (IAAC). He has worked as faculty and researcher at FabLab Barcelona and the IAAC, as director at FabLab Seoul, faculty at CEU San Pablo University of Madrid, and at the University of Architecture, Civil Engineering and Geodesy of Bulgaria.
- **Taizhong Chen** is a senior designer at Zaha Hadid Architects' Computation and Design group (ZHA CODE). He specialises in computational geometry and robotic fabrication for architecture, developing design toolsets to deliver structurally optimised and fabrication efficient projects. Taizhong completed his Master's degree at the Architectural Association Design Research Lab in 2019. He is an active participant in academic forums, teaching and presenting at international workshops and CAD conferences.
- **Tiffany Cheng** is a computational designer and builder at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart. Her research focuses on material programming for bioinspired self-shaping and developing computational fabrication tools for 4D printing. Before joining the ICD in 2017, Tiffany worked as an architectural designer at Studio Fernando Vazquez in Marina del Rey, and as a researcher at the MaP+S Group at the Harvard Graduate School of Design.
- **Nikoletta Christidi** is a PhD candidate at TU Delft, the Netherlands. Her interests lie at the intersection of architecture, engineering, and computer science, with an emphasis on structural design and digital fabrication. Her PhD research is supervised by Mariana Popescu and Christian Louter and focuses on designing CNC weft-knitted textiles, tailored for specific geometries and mechanical behaviours, for architectural and construction applications.
- **Julie Corneliusen** is a structural engineer and computational designer at Rambøll in Copenhagen, where she has worked since January 2021. Her professional pursuit is to encourage computational design and interdisciplinary design collaboration for better informed design decisions throughout the entire building process.
- **Alexander (Sandy) Curth** is a designer and researcher working to develop democratising technologies for low-carbon, low-cost construction with local materials. As a PhD candidate in the Design and Computation group at MIT, advised by Professor Lawrence Sass, he has created and published methods for large-scale additive manufacturing (AM) with earth. He works with the Digital Structures research group to produce prototypes for shape-optimised concrete structures as well as thermally performative building components.
- **Martyn Dade-Robertson** is Professor of Emerging Technology at Northumbria University, co-lead of the Living Construction research group, and a founder of the Hub for Biotechnology in the Built Environment (HBBE). His expertise extends across architectural design, computation, and synthetic biology. He has published more than 50 journal and conference papers, and two books: The Architecture of Information, and Living Construction. He is Editor in Chief of the journal Biotechnology Design and edits the Routledge book series Bio Design.
- **Niccolò Dambrosio** is a former research associate at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart. Dambrosio's research focuses on the use of anisotropic fibre composite materials in additive production processes for high-performance, lightweight structures. Presently, he is employed as computational designer at Adidas where his work is centred on the design and development of 3D-printed lattice structures for footwear products.
- **Barrak Darweesh** is an architectural and computational designer, at present attending UC Berkeley as a PhD candidate at the Building Science, Technology, and Sustainability Group. His research investigates the advancement of additive manufacturing (AM) and robotic construction at an architectural scale, with a particular focus on developing innovative software and hardware tools.
- **Anders E. Daugaard** is an Associate Professor in Polymer Chemistry at the Danish Polymer Centre, Department of Chemical and Biochemical Engineering, Technical University of Denmark (DTU). His research is dedicated to the synthesis of polymers and preparation of materials with a special focus on bio-based raw materials and the sustainable use of raw materials and products. His research activities target materials from biopolymers, bio-based polymer synthesis from impure starting materials, as well as improving the quality of recycled plastics or extending the lifetime and application span of materials through chemistry to reduce overall impact of materials.
- **Kate Davies** is Co-director of Design + Make and Head of Hooke Park. Her work explores the complexities of contemporary landscapes as they collide, disarranging the materiality of physical sites with the array of abstract and immaterial factors that accompany them. She is co-founder of the nomadic studio Unknown Fields. Her work has been exhibited internationally and is held in the permanent collections of leading museums. Prior to moving to Hooke Park, Davies was head of Media Studies at the Architectural Association (AA), and unit master of AA Diploma 6 (Unknown Fields). She has also taught MArch units at The Bartlett School of Architecture, UCL.
- **Dr Alessandro Dell'Endice** is a postdoctoral researcher at the Block Research Group (BRG), ETH Zürich. He studied structural engineering and architecture at the Politecnico di Bari (Italy) and digital fabrication at ETH Zürich, where he earned his PhD in 2022. He joined the BRG in 2016, and his work focuses on the structural assessment and design of unreinforced masonry structures using the Discrete Element Modelling method.
- **Benjamin Dillenburger** is Professor of Digital Building Technologies at the Institute of Technology in Architecture (ITA) at the Department of Architecture, ETH. His research focuses on the development of building technologies based on the close interplay of computational design methods, digital fabrication, and new materials. His work was presented at events such as the Venice Architecture Biennale, London Design Week, and Art Basel Miami. His projects include two full-scale 3D-printed rooms exhibited at the FRAC Centre Orléans, and the permanent collection of Centre Pompidou Paris, as well as the Smart Slab at the DFAB House in Switzerland.
- **Dr Kathrin Dörfler**, an architect, researcher, and educator in computational design and robotic fabrication. Her doctoral thesis, conducted at Gramazio Kohler Research, ETH Zürich, as part of the National Centre of Competence in Research (NCCR) Digital Fabrication, advanced methods for the use of construction robots directly on building sites. Since 2019, Dörfler has led a research group for Digital Fabrication at the Technical University of Munich (TUM) exploring the synergy between computational design and robotic fabrication.
- **Moritz Dörstelmann** is a Professor of Digital Design and Fabrication (DDF) at the Karlsruhe Institute of Technology (KIT) and founding partner of the robotic construction company FibR GmbH. His work investigates digital circular construction concepts at the interdisciplinary interface of research and teaching through explorative prototyping of innovative material systems and construction technologies. His construction company FibR realises resource-efficient fibre composite lightweight structures in architectural projects through computational design and robotic fabrication at an industrial scale.
- **Alexandre Dubor** is an architect and researcher who explores the potential of new technologies, materials, and designs to contribute to a greener construction industry, with a focus on 3D printing and robotics for producing sustainable architecture. Since 2012, he has worked at the IAAC where he now leads the Robotics Lab, and directs 3dPA, a postgraduate programme researching 3D printed architecture, as well as the Master's in Robotics and Advanced Construction (MRAC).
- **Albert Dwan** is a senior acoustic engineer at the consulting firm Arup Deutschland GmbH. He graduated from Johns Hopkins University with a Master's in Audio Sciences in 2010, and has been professionally active as an acoustic consultant, designer, and researcher from 2010 until the present. His research focus areas lie in sustainable alternatives for acoustic treatments, as well as the subjective experience and psychological interpretation of indoor acoustic environments, also referred to as Soundscape studies.
- **Nik Eftekhar** is a PhD researcher at the Chair of Digital Building Technologies, ETH Zürich. He studied architecture at the Polytechnic University of Madrid (ETSAM, UPM). Since completing his MArch in 2018 and his MAS DFab in 2019, he has collaborated with Gramazio Kohler Research (GKR) to bring Mesh Mould to industry. From 2021 to 2023 he has worked at Nagami as a computational designer and large-scale robotic polymer 3DP specialist.
- **Heba Eiz** is a researcher at Zaha Hadid Architects' Computation and Design group (ZHA CODE). She completed her MSc in Architectural Computation at The Bartlett UCL in 2021. Her expertise lies in implementing computational workflows for efficient realisation of commercial and research projects, with a particular focus on architectural geometry, parametric modelling, and coordination. Eiz's work involves contributing to the development of a state-of-the-art, proprietary computational code framework emphasising language and software interoperability and user API.
- **Jonas Elding** is a co-founder of Elding Oscarson Architects, a Stockholm-based studio working at various scales from product design to public buildings. The studio has received several national and international awards, such as the highest honour in Swedish architecture, the Kasper Salin Prize. In the Wisdome Stockholm project they dared to step out of the orthogonal by proposing a free form, challenging themselves, the client, and as it turned out, even the Nordic timber building industry.
- **Carl Eppinger** is a designer and digital fabrication research assistant at the Centre for Information Technology and Architecture (CITA) at the Royal Danish Academy, Copenhagen. He specialises in robotic fabrication with a concentration on additive manufacturing (AM) for biopolymers. He holds a Master's in Architecture from the University of Michigan Taubman College of Architecture and Urban Planning, as well as a Master of Science in Architecture Design and Research from the Rackham Graduate School, University of Michigan.
- **Max Benjamin Eschenbach** is a computational design researcher focused on the development of digital process chains as well as interactive and collaborative tools for design, planning, and fabrication. He is a research associate

and PhD candidate at the Technical University of Darmstadt within the Digital Design Unit (DDU), conducting research on computational tools for architectural design with reused components. Eschenbach studied product design at the University of Kassel (Kunsthochschule Kassel), where he worked in research and teaching within the workshop for Digital Design and Fabrication (Digitale 3D-Technik), from 2019 to 2021.

- **Philipp Eversmann** is an architect and professor at the University of Kassel, leading the Department of Experimental and Digital Design and Construction. His research group focuses on digital design and construction methods using sustainable materials and robotic additive manufacturing processes. He was head of Education at the National Center of Competence in Research NCCR Digital Fabrication at ETH Zürich 2014–16.
- **Lachlan Fahy** is a London-based designer. He holds a MArch in Design for Manufacture from The Bartlett School of Architecture, UCL. With a foundation in industrial design, he earned his Bachelor's degree in Product Design from the Parsons School of Design. Fahy is dedicated to creatively tackling contemporary challenges through design innovation to make a positive impact.
- **Kiley Feickert** is an architect pursuing her PhD in Building Technology and a member of the Digital Structures research group at MIT. Feickert's objective is to develop ways to reduce embodied carbon in buildings through the critical evaluation of business-as-usual construction materials and methods. Her research focuses on optimising structural systems for material efficiency and reusing structures to reduce carbon emissions and increase access to affordable construction.
- **Daniel Fischer** studied architecture in Karlsruhe, Tampere, and in 2018 graduated with a degree in Digital Design and Architecture at TU Delft. After several years as a project architect, he joined the Professorship for Digital Design and Fabrication (DDF), Karlsruhe Institute of Technology (KIT), in 2021, with a particular research interest in digital wood construction and circular economy. In 2022, Fischer became a licensed and registered architect.
- **Dr Robert J. Flatt** is Professor of Physical Chemistry of Building Materials at ETH Zürich, having held the position since 2010. Before that he was Principal Scientist at Sika Technology AG for eight and a half years, and a postdoctoral researcher at Princeton University for two and a half years. He holds a Master's in Chemical Engineering and a PhD from École Polytechnique Fédérale de Lausanne (EPFL). His principal research topic is to investigate the working mechanisms of chemical admixtures, which can be considered the 'spices' of concrete.
- **Julia Fleckenstein** has been a research associate at the Professorship of Digital Fabrication at the Technical University of Munich (TUM) since 2019. She holds an architecture degree from the University of Innsbruck and gained experience as a scholarship student at the University of Texas at Arlington, and at the Southern California Institute of Architecture. Her doctoral research explores computational design methods and their application in robotic fabrication with a focus on geometrically differentiated and site-specific building envelopes.
- **Eduardo (Edu) Gascón Alvarez** is an architect and researcher working on ways to achieve a thermally comfortable built environment at minimal material and energetic cost. He is a PhD candidate in the Building Technology group at MIT. His research focuses on the design and simulation of low-carbon building components that improve the resiliency of buildings to heat.
- **Dr Lukas Gebhard** is a postdoctoral researcher in the field of digital fabrication with concrete, focusing on structural applications. In 2018, he completed his Master's in Civil Engineering, with Distinction, at ETH Zürich. After graduation, he began his doctorate, titled Reinforcement Strategies for Digital Fabrication with Concrete, under the supervision of Professor Dr Walter Kaufmann in the Chair of Concrete Structures and Bridge Design at ETH Zürich. In 2021, he was a research fellow at the University of Naples Frederico II.
- **Katie Gilmour** is a microbiologist, currently working as a senior researcher at Northumbria University. She is also a member of the Hub for Biotechnology in the Built Environment (HBBE). She has years of experience working with engineered living materials, in particular bacterial cellulose, and has published on functionalising bacterial cellulose using an engineered biology approach.
- **Monika Göbel** is a registered architect in Stuttgart and a research associate at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart. She holds an MSc degree from Columbia University NYC, and a diploma-engineering degree from the University of Applied Science Kiel. Prior to joining the ICD, Göbel gained professional experience as an architect and project manager at KUKUK Freiflug Stuttgart, Atelier Brückner Stuttgart, Hannes Wettstein Zürich, Foster and Partners London, and Eisenman Architects NYC.
- **Fabio Gramazio** is an architect with multi-disciplinary interests ranging from computational design and robotic fabrication to material innovation. In 2000, he founded with Matthias Kohler, the architecture practice Gramazio & Kohler, where numerous award-winning designs have been realised. Bridging architectural practice and research, their projects include 1:1 prototype installations and design of robotically fabricated high-rises. Their research has been formative in the field of digital architecture, setting precedence and de facto creating a new research field merging advanced architectural design and additive fabrication processes through the customised use of industrial robots.
- **Dr Guillaume Habert** graduated in 1999 from the Ecole Normale Supérieure in Paris with a degree in earth, atmospheric and oceanic studies. After his PhD in structural geology, he explored specific clays and pozzolans as a cement substitute. Between 2007–12, he conducted research at the Laboratoire Central des Ponts et Chaussées in Paris, focusing on sustainable concrete and environmental evaluation of building materials. He is currently a full professor of the Chair of Sustainable Construction at ETH Zürich and has contributed to more than 100 scientific papers.
- **Michael Hansmeyer** is an architect and programmer active in the fields of computational design and digital fabrication. Recent projects include the construction of a muqarna for Mori Art Museum near Tokyo, and an installation for BMW Art Club. He has exhibited at museums and venues including the Museum of Arts and Design New York, Palais de Tokyo, Martin Gropius Bau, and Design Miami / Basel. His work is part of the permanent collections of Centre Pompidou and FRAC Centre. He has taught at the Academy of Fine Arts Vienna, Southeast University Nanjing, and ETH Zürich.
- **Matthias Klith Hardarson** studied architecture at the Aarhus School of Architecture (AARCH), where he has since worked as a teaching and research assistant with a specialisation in parametric design and digital fabrication. His work has primarily focused on wood-based projects, emphasising the utilisation of materials from various waste streams, which has resulted in the production of a series of material experiments and pavilions.
- **Tamara Haußer** is a research associate and a PhD candidate at the Institute for Design of Structures (dos) at the Karlsruhe Institute of Technology (KIT). Before joining dos, she worked as a structural engineer at Leonhardt, Andrä and Partner (LAP) in Stuttgart. Her research at present focuses on designing and developing innovative hybrid building systems that combine natural materials such as timber, clay, and natural fibres.
- **Dirk E. Hebel** is Professor of Sustainable Construction and Dean of the Department of Architecture at the Karlsruhe Institute of Technology. He is the author of numerous book publications, lately *Urban Mining und kreislaufgerechtes Bauen* (2021, Fraunhofer Verlag, with Felix Heisel). He is co-founder and partner of 2hs Architekten und Ingenieur PartGmbB Hebel Heisel Schlesier, focusing on resource-respectful construction. Together with Professor Andreas Wagner, he won the first Solar Decathlon Competition 2022 held in Germany with the team RoofKIT.
- **Friedrich Herding** works as a researcher at the Institute of Building Materials (iBMB), Technische Universität Braunschweig (TUBS). He studied civil engineering at RWTH Aachen University before relocating to Braunschweig in 2020. At present, his research focuses on the interaction between materials and processes in particle bed 3D printing with selective cement activation.
- **Duncan Horswill** is a structural engineer and design director at Rambøll in Copenhagen. He has more than 25 years of experience with building design and has worked in both engineering and architectural practices in the UK and in Denmark. His interest lies in the collaborative design process and how engineering can positively impact the architectural concept in the early stages to create buildings that are meaningful, functional, and sustainable.
- **Marco Hutter** is an Associate Professor of Robotic Systems with ETH Zürich. He is also a part of the National Centre of Competence in Research (NCCR) Digital Fabrication and the principal investigator in various international projects and challenges. His research interests include the development of novel machines and actuation concepts together with the underlying control, planning, and machine learning algorithms for locomotion and manipulation.
- **Vincent Huyghe** is a robotics expert and faculty at the Institute of Advanced Architecture of Catalonia (IAAC). His areas of specialisation are computational geometry, DFMA, and robotic manufacturing, along with possessing a comprehensive knowledge across a range of topics such as electronics, numerical manufacturing, robot cell design and integration, robotic process automation, systems engineering, and scripting. He has previously taught at The Bartlett School of Architecture (UCL)
- **Dr Mohamed Ismail** is an Assistant Professor of Architecture at UVA School of Architecture. He completed his PhD in the Building Technology programme at MIT, where he studied the application of structural and material optimisation in the alleviation of housing insecurity in the Global South with the Digital Structures research group. His research is published in many authored and co-authored papers for peer-reviewed journals and conferences.
- **Dr Alireza Javadian** is presently working as the head of research in the Faculty of Architecture at Karlsruhe Institute of Technology in Germany and as the co-principal investigator of the Urban Bio-cycle project at the Future Cities Laboratory, Singapore. His research is focused on the development of alternative sustainable construction materials made from renewable resources such as bamboo, timber and agricultural waste, and industrial by-products, following a circular economy principle.
- **Romy Kaiser** is a bio-designer and researcher focusing on biomaterials, textile thinking, and fibre-based bio fabrication methods. She holds a PhD position at the Hub for Biotechnology in the Built Environment, Newcastle University, UK, working at the intersection between biology, textiles, and architecture as part of the Living Textiles research group. Kaiser's research project Knit- Mycelium Hybrids investigates the scaffolding potential of knitted textiles for mycelium growth.
- **Mette Marie Kallehauge** holds a Master of Arts degree in Art history and visual culture and has been a curator at Louisiana Museum of Modern Art since, 2009. She has co-curated the exhibition series 'The Architects Studio', the last exhibition of which showcases the work of Cave_bureau.
- **Ananya Kango** is an architect with a background in multi-scalar digital fabrication. He finished his MAS ETH DFAB in 2022 and has since been working with Gramazio Kohler Research ETH. His interests lie in robotic control systems, large-scale additive manufacturing techniques, and novel material processes. He focuses on developing customised tools and algorithms suited for architecture and construction applications.
- **Kabage Karanja** is an architect, spelunker and adjunct assistant professor at Columbia University's Graduate School of Architecture Planning & Preservation, GSAPP. He founded Cave_bureau in 2014 alongside Stella Mutegi.
- **Paul Kassabian** is a principal at Simpson Gumpertz & Heger (SGH), in Boston, Massachusetts. He is experienced in structural design and investigation of a wide range of structural systems, from historic buildings to projects on the cutting edge of structural systems and materials. He focuses on developing innovative methods of design and construction using SGH's in-house materials lab and digital design approaches. Paul lectured at MIT, then Harvard, and now at the Rhode Island School of Design (RISD).
- **Walter Kaufmann** is the Chair of Concrete Structures and Bridge Design at ETH Zürich. He is a lead PI in the Swiss National Centre of Competence in Research (NCCR) Digital Fabrication (DFAB), a steering committee member of the Design++ initiative and Immersive Design Lab, and presides over the Swiss Concrete Code Commission. His research focuses on innovative structures, the modelling of concrete structures, the assessment of the structural safety of existing structures, and digital fabrication.
- **Laura Kiesewetter** is a research associate at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart. Her research focuses on advanced computational design and construction technologies of novel material systems and their integration in the built environment. She is especially interested in materially programmed lightweight timber structures that self-shape.
- **Kjeld Kjeldsen** graduated as an architect from the Aarhus School of Architecture in the early 1970s and has been affiliated with the Louisiana Museum of Modern Art since 1985. As curator and museum inspector, Kjeld has organised an impressive series of ground-breaking art and architecture exhibitions of international caliber.
- **Marirena Kladeftira** is a PhD researcher at the Chair of Digital Building Technologies, ETH Zürich, where she leads the research on additive-manufactured complex joints for bespoke lightweight structures. Her work has been exhibited at various venues and events, including the Venice Biennale and the ZAZ Bellerive Museum in Zürich. Before joining ETHZ, she was a visiting researcher at the Transformable Intelligent Environments Laboratory at the Technical University of Crete (TUC).
- **Harald Kloft** is Professor for Structural Design at the Technical University of Braunschweig (TUBS). As co-founder of the engineering firm Office for Structural Design (osd), he has wide experience in the realisation of non-standard structures. Together with his team at the Institute of Structural Design (ITE), he researches innovative digital manufacturing technologies for the construction sector. Since 2020, Kloft has been spokesperson of the DFG Collaborative Research Centre TRR 277 Additive Manufacturing in Construction at the technical universities of Braunschweig and Munich.
- **Jan Knippers** is head of the Institute for Building Structures and Structural Design (ITKE) at the University of Stuttgart, and a consulting structural engineer. His interest is in innovative and resource-efficient structures at the intersection of research development and practice. In addition to advanced wood and fibre structures, bio-inspired compliant mechanisms are one of his principal research topics. Since 2019, he has been Deputy Director of the Cluster of Excellence Integrative Computational Design and Construction (IntCDC), and from 2021 to 2023, Dean of the Faculty of Architecture.
- **Bruno Knychalla** studied architecture and digital building technologies at the Technical University of Munich (TUM), and at the University of Stuttgart. He is co-founder and managing director of additive tectonics GmbH and a board member of the CyberCraft Institute (CCI), both situated in Bavaria, Germany. Since 2020, additive tectonics GmbH has worked on developing and applying a broad range of architectural 3D printing technologies.
- **Matthias Kohler** is an architect with multi-disciplinary interests ranging from computational design and robotic fabrication to material innovation. In 2000, he founded with Fabio Gramazio the architecture practice Gramazio & Kohler, where many award-winning designs have been realised. Bridging architectural practice and research, their projects include 1:1 prototype installations and the design of robotically fabricated high-rises. Their research has been formative in the field of digital architecture, setting precedence and de facto creating a new research field merging advanced architectural design and additive fabrication processes through the customised use of industrial robots.
- **D.I. Reinhard Kropf** studied at TU Graz and AHO under Sverre Fehn. Together with Siv Helene Stangeland he founded Helen & Hard in 1996 which today has offices both in Stavanger and Oslo, Norway. He has taught at various institutions, including Kansas State University, L'École d'Árchitecture in Paris, the Bartlett UCL in London, Hust University in Wuhan, TUM in Munich and AHO in Oslo. He delivers lectures worldwide about H&Hs work and extensively publishes, particularly focusing on the firm's engagement with sustainability and timber architecture.
- **Anders Kruse Aagaard's** research focuses on materials and material processing in relation to architectural design and construction. This includes materials behaviours and their effect on design and design potential, as well as the connection between design, design representation, and machined reality. Materials and machining are investigated primarily through digital fabrication technologies on the preceding digital and computational design, modelling, and workflows.
- **Christoph Kuhn** is an architect and professor at the Technical University of Darmstadt, where he heads the Design and Sustainable Building (Entwerfen und Nachhaltiges Bauen; ENB) department. His teaching and research revolve around the design, planning, construction, and operation of sustainable buildings. In 2015, he co-founded the architecture practice Kuhn und Lehmann Architekten in Freiburg. He was professor at the Department of Sustainable Building and Integrative Design at Karlsruhe Institute of Technology (KIT) from 2010–13.
- **Riccardo La Magna** is a structural engineer active in both research and practice. As an engineer he focuses on the development of advanced technological projects, which make use of innovative materials and advanced fabrication techniques. Since 2021, he has held the role of professor at the Karlsruhe Institute of Technology (KIT), where he leads the Institute for Design of Structures (dos). In his research he focuses on simulation technology, innovative structural systems, and new materials for building applications.
- **Anja Patricia Regina Lauer** received her BSc in Engineering Cybernetics in 2017, and her MSc in Engineering Cybernetics in 2019, from the University of Stuttgart. She was also awarded MEng in Mechanical Engineering at the Toyohashi University of Technology, Japan, in 2019. She is a research assistant and PhD student at the Institute for System Dynamics, University of Stuttgart, where her research interests include large-scale manipulators, construction robotics, and automated on-site assembly.
- **Lukas Ledderose's** research focuses on the construction of load-bearing structures from reused building elements. He studied architecture at the Karlsruhe Institute of Technology (KIT), from 1999 to 2006, and at the Städelschule in Frankfurt am Main (SAC) from 2008 to 2010). He has worked in architectural offices such as Studio Zhu Pei, Beijing, China (2007), and Architekturbüro Kluth, Neuss (2008). Today he works as a postdoctoral researcher at the Institute for Structural Design (ITE) at the Technical University of Braunschweig.
- **Sunbin Lee** is a PhD researcher and designer who's primary research focus involves exploring the role of living matter in architecture, ranging from nano to macro-scale, by applying advanced biotechnology, synthetic biology, and material sciences employing computation and digital fabrication, for the utilisation of microspecies. His work is dedicated to the development of a cell-based bio-fabrication approach that enables biological-digital interactions, thereby allowing living cells to be functionalised to exhibit novel material properties.
- **Matthias Leschok** is a PhD researcher at the Chair of Digital Building Technologies, ETH Zürich. His work investigates high-performance 3D printed façades systems and is the author of a patented 3D printing technology. He has exhibited at the Venice Biennale and the ZAZ Bellerive Museum in Zürich. He is co-founder and COO of SAEKI Robotics AG, an ETH spin-off developing decentralised production hubs for large-scale bespoke elements.
- **Ayoub Lharchi** is a registered Architect and Computational Designer with a specialised interest in design for assembly and the integration of intricate architectural components. Lharchi has amassed experience across many countries, having worked and taught in Germany, the US, Denmark, Switzerland, and Belgium. His latest research emphasises information modeling for Design for Assembly in architecture, seeking to optimise and revolutionise contemporary design processes.
- **Che-Wei Lin** is a scientific assistant in the Chair of Digital Building Technologies, Institute of Technology in Architecture, ETH Zürich. After graduating from Feng Chia University in Taiwan, he worked as a researcher at ROSO COOP Robotic Solutions, focusing on robotic fabrication and autonomous construction robotics. In 2021, he pursued the MAS Digital Fabrication programme at ETH Zürich. His thesis, Pneuprint, investigated the fabrication technique that uses inflatable membranes to support 3D printed elements.
- **Joshua Loh** is a postdoctoral research associate at Northumbria University, with a keen interest in harnessing biotechnology for a sustainable future. His research is centred on the functionalisation of living materials through engineered biology. With a background in biotechnology and a passion for innovation, he is dedicated to exploring applications in the field of synthetic biology and engineered living materials.
- **Leslie Lok** is an assistant professor at Cornell University Department of Architecture and directs the Rural-Urban Building Innovation Lab. By integrating digital construction methods with non-standardised materials and local material resources, her work customises visualisation, design, and fabrication workflows for novel material

methods. Lok is also a co-founder at HANNAH, an experimental design practice in Ithaca, New York.

- **Dr Hélène Lomboise-Burger** is the research and development (R&D) head for Concrete and Aggregates, and Digital Fabrication at Holcim. Her role focuses on the development of innovative market solutions with a strong focus on sustainability, in a collaborative ecosystem spanning the entire value chain. She holds an engineering degree (ESPCI ParisTech, 2000) and a PhD in Materials Science (Paris 6 University, 2003). She is author of more than 25 publications/patents.
- **Brian Lottenburger** is member of the Danish Association of Architects. He graduated with an M.Arch degree from the Royal Danish Academy of Fine Arts, School of Architecture, Denmark, in 2005. Brian has been affiliated to Louisiana Museum of Modern Art as exhibition architect since 2013.
- **Dirk Lowke** is an expert in building materials and additive manufacturing (AM) in construction. From 2006–17, he was head of the Concrete Technology Group at the Technical University of Munich (TUM). From 2017–23 he was full professor at the Technische Universität Braunschweig (TUBS), Department of Building Materials. Since October 2023 he has been appointed full professor at the Technical University of Munich, Department of Building Materials.
- **Grzegorz Malczyk** received his MSc in Robotics, Systems and Control in 2022 from ETH Zürich, Switzerland. He is pursuing a PhD at Autonomous Robots Lab, NTNU, Norway. Previously, from 2022 to 2023, he was a research engineer in the Robotic System Lab at ETH Zürich. His research interests focus on the motion planning and control of aerial and ground robots and multi-robot systems, aiming to develop novel algorithms and techniques for operating autonomously in real-world applications.
- **Dr Mathilde Marengo** is an architect who's research sits at the critical intersection of planetary urbanisation, the climate crisis and advanced technological development. She is head of the Master's programme in City and Technology studies, as well as co-director, faculty, and PhD supervisor at the Institute for Advanced Architecture of Catalonia (IAAC), and part of its Advanced Architecture Group, investigating emerging technologies of information, interaction, and manufacturing for the design and transformation of cities, buildings, and public spaces.
- **Niels Martin Larsen** is an associate professor at Research Lab 2, Technology, Building Culture, and Habitation at the Aarhus School of Architecture (AARCH). Larsen's research is internationally acknowledged and oriented towards engaging alternative wood resources in architecture, thereby supporting biodiversity, reducing carbon emissions, and expanding the material vocabulary. Larsen established the Artic Wood Architecture Network and is presently engaged in researching new ways of using irregular natural wood and discarded materials from the wood industry as well as digital technology for reusing existing buildings.
- **Dinorah Martínez Schulte** is Mexican architect and researcher who obtained her degree in architecture from the Universidad Iberoamericana, Mexico City. Martínez has collaborated with renowned firms such as MAD Architects and ENSAMBLE Studio. She is co-founder of MANUFACTURA, and an adjunct associate professor at Universidad Iberoamericana as well as Universidad La Salle in Mexico City. She is a member of the editorial board of CEMEX México 2023.
- **Wes McGee** is Associate Professor in Architecture and director of the Fabrication and Robotics Lab at the University of Michigan Taubman College of Architecture and Urban Planning, and a principal at Matter Design. His research involves the interrogation of design and material production in architecture, with the goal of developing new connections between design, engineering, materials, and manufacturing processes as they relate to the built environment.
- **Johannes Megens** is co-founder and co-CEO of incremental3d LLC, an Austrian Spin-Off company that focuses on 3D concrete printing. After completing his architecture studies he continued to follow his interest in computational design and research on robotic fabrication methods as a researcher at the faculty of architecture, at the University of Innsbruck. In 2017, after conducting early and pioneering research in 3D concrete printing, incremental3d was founded, and Megens has been working in the field of 3DCP ever since.
- **Achim Menges** is a registered architect in Frankfurt and full professor at the University of Stuttgart, where he is the founding director of the Institute for Computational Design and Construction (ICD) and the director of the Cluster of Excellence Integrative Computational Design and Construction for Architecture (IntCDC). In addition, he has been Visiting Professor in Architecture at Harvard University's Graduate School of Design and held multiple other visiting professorships in Europe and the US. He graduated with Honours from the Architectural Association, London.
- **Dr Fabian Meyer-Broetz** is the Managing Director of PERI 3D Construction Printing, part of the PERI Group, one of the largest manufacturers of formwork and scaffolding solutions in the world. His work revolves around paving the way for a broader application of 3D printing in industrial practices and bringing state of the art technology to real world construction sites. He received his Master's in Physics and a PhD in Economics from the University of Ulm.
- **Loic Regnault de la Mothe** is a team leader and research and development (R&D) engineer at Holcim Innovation Centre in Lyon, France. He is responsible for mix-designing of mortars and concretes for additive manufacturing applications. He joined Holcim in 2021 after a career in the oil and gas industry primarily dedicated to oil well cementing R&D. In 2001, he graduated from Ecole Superieure de Physique et de Chimie (ESPCI), the French engineering school in Paris.
- **Caitlin Mueller** is an associate professor in the departments of Architecture and Civil and Environmental Engineering, in the Building Technology programme at MIT, where she has led the Digital Structures research group since 2014. She works at the creative interface of architecture, structural engineering, and computation, and focusses on new computational design and digital fabrication methods for innovative, high-performance buildings and structures that empower a sustainable and equitable future.
- **Stella Mutegi** is an architect, spelunker and adjunct assistant professor at Columbia University's Graduate School of Architecture Planning & Preservation, GSAPP. She founded Cave_bureau in 2014 alongside Kabage Karanja.
- **Dr Serge Nana** is a research scientist at Holcim Innovation Center. He holds a Master's in Structures and Materials (2014, INSA Lyon), and a PhD in Mechanics of Structures (2017, INSA Lyon). He has worked as research and development (R&D) manager, leading innovative projects such as 3D printing, UHPFRC, and carbon efficient construction. He teaches part-time at university on structural mechanics and numerical modelling. He believes the price of progress is that we must dare to change things.
- **Catie Newell** develops material and optical assemblies that amplify our connection to a living and spinning earth. As the founding principal of the architecture and research practice Alibi Studio and an Associate Professor of Architecture at the University of Michigan, Newell's research and creative practice has been widely recognised for exploring design construction and materiality in relationship to location and geography. She deploys material behaviour, illumination and darkness, and novel modes of occupation.
- **Paul Nicholas** is Associate Professor at the Centre for Information Technology and Architecture (CITA) at the Royal Danish Academy, Copenhagen. His recent research investigates advanced fabrication for biogenic materials, applies machine learning to manufacture, and explores how sustainable and circular resource flows drive new architectural perspectives. Nicholas is director of the international Master's programme Computation in Architecture.
- **Moritz Niebler** is consultant at Design-to-Production Zürich, developing digital fabrication and planning solutions for complex timber structures. Trained as an architect and carpenter he works at the interface between architects, engineers and contractors with a focus on both computational design and design for manufacturing and assembly. Since 2021, he has been involved in the parametric planning for several large-scale timber structures, such as the Wisdome project in Stockholm.
- **Nadja Nolte** is a research associate from the Experimental and Digital Design and Construction chair (EDEK) at the University of Kassel. In 2019 she co-founded the BIOLAB at the Art School, a platform for designing and researching at the interface of design, art, and biology. She is presently researching the combination of sustainable, growing materials with computational design and digital fabrication strategies.
- **Eszter Olah**, a research engineer at the Professorship for Digital Design and Fabrication (DDF) at the Karlsruhe Institute of Technology (KIT). Olah's primary research focus is on developing and refining fabrication processes that utilise natural materials. Prior to her current role, Olah refined her research methods and practical engineering skills through research internships and at an engineering consultancy.
- **Nils Opgenorth** is a research associate at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart. Prior to joining ICD, he taught at the Institute for Digital Methods in Architecture in Hannover. At present, his attention is directed to developing a fabrication system for a heterogeneous multi-scalar robotic construction system, aiming to enhance the automation of on-site timber construction.
- **Dr Maximilian E. Ororbia** is a postdoctoral fellow at the Weitzman School of Design, University of Pennsylvania, in the Polyhedral Structures Laboratory (PSL). His research includes developing architectural, engineering, and construction design, decision-making, optimisation processes, and fabrication technologies, as well as creating computational tools aided by machine learning for generating and exploring design spaces.
- **Johan Oscarson** is a co-founder of Elding Oscarson Architects, a Stockholm-based studio working at various scales from product design to public buildings. The studio has received several national and international awards, such as the highest honour in Swedish architecture, the Kasper Salin Prize. In the Wisdome Stockholm project they dared to step out of the orthogonal by proposing a free form, challenging themselves, the client, and as it turned out, even the Nordic timber building industry.
- **Eda Özdemir** is a research associate at the Experimental and Digital Design and Construction chair (EDEK), University of Kassel. She obtained a Bachelor of Science at Politecnico di Milano in 2017, and a Master of Science from the ITECH programme at the University of Stuttgart in 2020. Her research focuses on large-scale additive manufacturing and novel digital fabrication methods utilising sustainable materials, most currently on reinforced mycelium composites.
- **Dilan Ozkan** is an architect and researcher focusing on working with non-linear materials. At present, she is a PhD student and research assistant in the Hub for Biotechnology in the Built Environment at Newcastle University, UK. Within her research, she is developing a design framework and bio digital fabrication method to guide the growth of living materials. During her PhD, she formed a study group called Mycology for Architecture to collaborate with other disciplines and share knowledge about fungi.
- **Karolina Pajak** is a department leader of the research and development (R&D) 3D printing team at Sika Technology AG, in Zürich, Switzerland. In her role, Pajak focuses on the structural applications of 3D concrete-printed objects, automation of the construction processes, and the development of new 3D-printed materials. With her team, she aims to bring innovation and automation to the construction market.
- **Dr Marta Gil Pérez** is a postdoctoral researcher and research group leader at the Institute of Building Structures and Structural Design (ITKE), University of Stuttgart. Gil Pérez extended her professional experience as a project engineer at C.S. Structural Engineering in South Korea participating in the structural design of projects in South Korea and the Middle East. Thereafter, she joined ITKE and obtained her PhD in Engineering. Her research interests lie in the structural design of nonstandard building systems, focusing on sustainability and co-design.
- **Gerrit Placzek** is a researcher at the Institute of Construction Engineering and Management (IBB) at Technische Universität Braunschweig (TUBS). From 2012–18 he studied civil engineering at TUBS and remained in academia to delve into the digitalisation of planning and construction processes and the changing system boundaries of the construction industry. Since 2019 he has worked on the implementation of additive manufacturing (AM) in the construction industry and on developing new concepts for Building Information Modeling (BIM)-based construction logistics.
- **Dr Mariana Popescu** is Assistant Professor of Digital Fabrication at TU Delft, the Netherlands, in the Faculty of Civil Engineering and Geosciences. She is a computational architect and structural designer with a strong interest and experience in innovative ways of approaching the fabrication process and use of materials in construction. She obtained her PhD from ETH Zürich focusing on a novel flexible formwork system using 3D knitting.
- **Dr Olga Popovic Larsen** is an architect and Professor of Structures and Materials, and head of the Master's programme Arkitekturens Teknologi at the Royal Danish Academy in Copenhagen. Her research explores the crossover between aesthetics and structural/material efficiency, investigating materials in innovative ways, seeking to reveal how the artistic and the technological can inform each other and contribute to sustainable building practice.
- **Mandi Pretorius** is an architect, researcher and Ph.D. Candidate at the Yale School of Architecture and Yale Center for Ecosystems + Architecture. Her research explores how socio-ecological constructs in the built environment shape resource flows underpinning scarcity, access, and need. Her work has been awarded funding from the U.S. Environmental Protection Agency, NSF Nanosystems Engineering Research Center for Nanotechnology-Enabled Water Treatment, and The Whitney and Betty MacMillan Center for International and Area Studies.
- The work of **Ronald Rael** blurs the borders between architecture, art, technology, land-based practices, and social justice, including innovative processes for the robotic construction of raw earthen buildings. His work can be found in the permanent collections of the MOMA, the Cooper Hewitt Smithsonian Design Museum, the Design Museum, LACMA, the San Francisco MOMA, and the Renwick Smithsonian American Art Museum. He is the Chair of the Department of Art Practice and Eval Li Memorial Chair in Architecture at the University of California Berkeley.
- **Dr Arianna Rech** is a postdoctoral researcher at the Danish Polymer Centre, Department of Chemical and Biochemical Engineering, Technical University of Denmark (DTU). Her research is dedicated to the development of bio-based materials for the substitution of fossil-based materials, extending the lifetime of plastic materials through recycling. Latest projects are focused on biopolymer plasticisation and thermoprocessing, developing biopolymer composites with waste-derived lignocellulosic fillers, and understanding the degradation mechanism of plastic during the recycling process.
- **Shibo Ren** is a senior structural engineer from Arup Amsterdam with over 10 years of extensive experience leading complex projects across various scales in Europe. His practice and research are centred on the integral design of challenging structures, innovative material, and complex geometry, employing computational design strategies and digital fabrication for thinking, analysing, and designing.
- **Katja Rinderspacher** is a research associate at the Institute for Computational Design and Construction (ICD), and coordinator of the Integrative Technologies and Architectural Design Research (ITECH) MSc programme at the University of Stuttgart. She has gained professional experience as an architect and project manager in offices in the US, Switzerland, and Germany. Her research focuses on the design and development of high-resolution surface structures with indeterminate fabrication processes.
- **Dr Andrea Rossi** is an architectural researcher and computational designer at the Experimental and Digital Design and Construction chair (EDEK) at the University of Kassel. His research focus is on computational design, robotic fabrication, and architectural biomaterials. Previously he held position as researcher at ETH Zürich, Coop Himmelb(l)au (Vienna), and IndexLab (Milan). He is a board member of the Fieldstations e.V. association. Additionally, he is the developer of Wasp, an open-source software toolkit for combinatorial and discrete modelling.
- **Dr Nazanin Saeidi** is head of research at the Chair of Sustainable Construction at Karlsruhe Institute of Technology and co-principal investigator in the Urban Biocycle project at the Future Cities Laboratory, Singapore-ETH Centre. In her PhD at Nanyang Technological University, she worked on 'Engineering microbes to sense and eradicate a human pathogen', which was published by the Nature Publishing Group. She has received multiple awards and in 2020 was named by MIT Technology Review as one of the 20 emerging innovators in the Asia Pacific region.
- **Ekin Sila Sahin** is a research associate and doctoral researcher at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart. As a part of the Material Programming research group at ICD, her research concentrates on bioinspired weather-responsive façades (Solar Gate), upscaling 4D printing, and integrated computation. Her work focuses on the development of computational design methods and software that utilises material properties, behaviours, and multifaceted performance criteria to drive self-shaping design processes.
- **Sandro Sanin** joined incremental3d LLC, an Austrian Spin-Off company that focuses on 3D concrete printing, in 2018 as a student worker helping in production. Since then, his area of responsibility has shifted to preparing toolpaths and developing design to fabrication workflows for 3D printing. At present he is working towards his Master's in Architecture at the University of Innsbruck.
- **Professor Oliver Sawodny** received his PhD from the University of Ulm, Germany, in 1996. In 2002, he became a full professor at the Technical University of Ilmenau, Germany. Since 2005, he has been the director of the Institute for System Dynamics, University of Stuttgart. His research interests include methods of differential geometry, trajectory generation, and applications to mechatronic systems.
- **Lotte Scheder-Bieschin** (formerly Aldinger) is a PhD candidate at the Block Research Group (BRG), ETH Zürich. She played leading roles in the award-winning ICD/ITKE Research Pavilion 2016/17, the BUGA Wood Pavilion 2019, and Urbach Tower. Her PhD research focuses on bending-active formwork systems for concrete shells, utilising an integrative computational, structural design, and fabrication approach to foster sustainable construction. It explores two pathways: splines, as demonstrated in the KnitNervi Pavilion 2022, and curved-crease unfoldable plates.
- **Fabian Scheurer** is co-founder of Design-to-Production, the planning-, consulting- and software-practice that has been closing the gap between digital design and digital production in architecture since 2007. Scheurer led the parametric planning of the Wisdome project in Stockholm after practicing on timber gridshells like the Centre Pompidou in Metz, and the Swatch Headquarters in Biel. Since 2023 he has been Research Professor of Building Technology and Fabrication at Munich University of Applied Sciences.
- **Christoph Schlopschnat** is a research associate at the Institute for Computational Design and Construction (ICD), and in the Cluster of Excellence (IntCDC) at the University of Stuttgart. Recently he led the development of the digital design framework for the livMatS Biomimetic Shell, which merged architectural design processes, fabrication, and construction constraints and requirements from both research and industry partners into a process-based full-scale digital twin.
- Since 2016 **Patrick Schwerdtner** has been head of the Institute for Construction Engineering and Management (IBB) at Technische Universität Braunschweig (TUBS) and managing partner of CEM Consultants GmbH. In addition to his research in additive manufacturing (AM), he has expertise in lean construction, risk management, and evaluation of construction productivity. As a leading team member of the Competence Center for Integrated Project Management (IPA), he is committed to establishing new guiding principles for project delivery systems.
- **Jane Scott** is a NUAcT (NU Academic Track) Research Fellow in the Hub for Biotechnology in the Built Environment at Newcastle University, UK, where she leads the Living Textiles research group. Her research positions textiles as a critical bio fabrication strategy in the development of biohybrid materials and composites for architecture. Through large-scale prototyping, her group has established the protocols for knit/mycelium architecture and the precedents for 100% waste resource for bio fabrication.
- **Martin Self** is design director and a founder of Xylotek, a UK-based firm designing and delivering non-standard timber structures. With a background in aerospace engineering, he is an engineer, geometer, and educator who has specialised in innovative timber structures since 2005. He was a founder member of Arup's Advanced Geometry Unit (2000–2006) and Director of Hooke Park (2010–2018), the Architectural Association's woodland campus for experimental timber architecture, where he was founder of the Design + Make Master's programme.

- **Eleni Skevaki** is a doctoral researcher at the Lab for Creative Computation, École Polytechnique Fédérale de Lausanne (EPFL). Before that, she was a research assistant for Digital Building Technologies, ETH Zürich, working on additive manufacturing (AM) with concrete and other materials. Her research explores human-robot interaction within heterogeneous construction teams.
- **Lior Skoury** is a research associate at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart. Prior to joining ICD, he worked as a lead computational designer in the Israeli construction start-up industry at Para-Group and Structure-Pal. His research interests lie in the interplay between design, fabrication, and data management. He is presently working on an application for fabrication control and distribution systems.
- **Konrad Sonne** is a research assistant at the Centre for Information Technology and Architecture (CITA) at the Royal Danish Academy, Copenhagen. He has an MA from the Royal Danish Academy in Computation in Architecture and a BSc from the Technical University of Innsbruck. His work focuses on digital design and fabrication, specialising in robotic fabrication that ranges from tool development to large-scale additive manufacturing (AM) processes.
- **Karl-Johan Sørensen** is a computational designer and researcher at MIT, where he is pursuing a dual Master's in Civil Engineering and Design and Computation. His research focuses on generative structural assemblies of odd, reused parts. Sørensen co-founded SAGA Space Architects and led the design and fabrication of LUNARK, a foldable origami moon habitat.
- **Dr Alejandro Giraldo Soto** is an experienced structural engineer with expertise in bridge and building design and has a strong background in academia, specialising in structural design and large-scale testing. He holds the position of senior researcher in the Chair of Concrete Structures and Bridge Design, and at the Swiss National Centre of Competence in Research (NCCR) Digital Fabrication (DFAB), ETH Zürich. Within the NCCR DFAB, he is focused on the performance of 3D printed concrete (3DPC) and the development of load-bearing 3DPC column concepts.
- **Dr Siv Helene Stangeland** is a Norwegian architect and researcher. Together with Reinhard Kropf, she founded the architecture office Helen & Hard in 1996. She has taught and lectured widely about H&H's holistic sustainable practices within co-housing and innovative timber structures. The practice has produced an extensive body of built work in timber, and has received many awards, including the Norwegian National Award for Building and Environmental Design. The studio designed the Nordic Pavilion for the Venice Biennale 2021.
- **Tim Stark** is a research associate in the Computational Wood Architecture research group at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart, a position he has held since 2020. Specialising in automated manufacturing systems for the timber construction industry, Stark leverages his expertise in the conceptual and comprehensive planning of processes. His work encompasses the development of robotic fabrication systems, as well as the design and engineering of end effectors for prefabrication, along with automated on-site assembly.
- **Tom Svilans** is an architectural designer, design consultant, and researcher, focusing on digital fabrication, materiality, and emerging technologies. He is currently an Assistant Professor at CITA (Centre for IT and Architecture) at the Royal Danish Academy in Copenhagen, Denmark. His research focuses on digital design across the timber value chain – from forestry to construction – and methods of integrating new imaging and information-communication technologies in the design and fabrication of engineered timber elements. As a consultant, he specializes in the computational modelling, design development, and fabrication coordination of complex timber structures.
- **Yasaman Tahouni** is a computational designer and a doctoral candidate at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart. Her research is focused on developing computational fabrication processes that merge design, additive manufacturing (AM), and biobased 'smart' materials to create programmable and adaptive shape-changing structures. She has worked as a researcher and an educator at MIT and ICD, and has recently joined Samsung as a computational designer at the Samsung Design and Innovation Centre.
- **Martin Tamke** is Associate Professor at the Centre for Information Technology and Architecture (CITA) at the Royal Danish Academy, Copenhagen. He pursues design-led research at the interface of computational design and its materialisation. He joined CITA in 2006 and focuses on computational strategies and technologies for the transformation of the building industry towards sustainable and circular practices based on biomaterials. In 2022 he was guest professor at the Cluster of Excellence, Integrative Computational Design and Construction for Architecture (IntCDC), at the University of Stuttgart. At present, he is guest professor at the Polytechnical University of Milano.
- **Javier Tapia**, an undergraduate in civil engineering specialising in structures at the City College of New York (CCNY), is a research assistant at the Advanced Building Construction Lab (ABC Lab). Dedicated to advancing structural design, Javier aspires to achieving a Master's degree in structural engineering and becoming a professional engineer. His active role in innovative research reflects a commitment to shaping the future of sustainable construction practices.
- **Yara Tayoun** is an architect and researcher specialising in digital and technology-driven transitions of circular processes in architecture and design. She combines research in both academia (3dPA coordinator at IAAC) and industry (head of research at Noumena). Tayoun gained experience on co-creating circular resource flows in cities with a focus on wood construction as part of the research project ReflowEU. Under this activity she established a startup incubator fostering the early-stage application of computational design and advanced technologies in construction.
- **Dilara Temel** is an architectural assistant at Dannatt Johnson Architects and is engaged in diverse projects, with a particular focus on reuse and renovation initiatives for the British Museum, Lambeth Council, and the Bedfordshire Estate. She completed her MArch Design for Manufacture at The Bartlett School of Architecture, UCL, after an undergraduate education at Istanbul Technical University. Temel's primary interests lie in digital and parametric design, spanning CNC machining, clay 3D printing, and traditional building techniques.
- **Teng Teng** is a PhD fellow in the Department of Architecture at the Weitzman School of Design, University of Pennsylvania. As an interdisciplinary researcher and designer, Teng Teng specialises in exploring and developing advanced manufacturing tools. His approach synthesises mechanical engineering, electronics, and materials science principles. He is keenly interested in integrated processes spanning design to manufacturing, striving to dismantle conventional boundaries and to cultivate more efficient and innovative manufacturing techniques.
- **Dr Oliver Tessmann** is an architect and professor at the Technical University of Darmstadt, heading the Digital Design Unit (DDU). His teaching and research revolve around computational design, digital manufacturing, and robotics in architecture. Previous positions include an assistant professorship at the Royal Institute of Technology (KTH) in Stockholm (2012-2015), a guest professorship at Staedelschule Architecture Class (SAC, 2008-2011), and working at the engineering office Bollinger + Grohmann in Frankfurt.
- **Simon Treml** is a registered architect in Germany and research associate at the Institute for Computational Design and Construction (ICD) and the Cluster of Excellence (IntCDC) at the University of Stuttgart. Before joining ICD, he gained professional experience as an architect and project manager. Treml's research focuses on developing design-to-fabrication methods for lightweight timber structures. In the *liv*MatS biomimetic shell, his role included the conceptualisation, planning, and implementation of the robotic prefabrication and manufacturing of the shell components.
- **Léon Trousset** is a civil engineer (MEng) specialising in structural analysis. He has worked for Sika Technology AG for almost three years in the research and development (R&D) team for 3D concrete printing (3DCP). His research focuses on finding ways to test the mechanical properties of 3DCP on small-scale elements to establish reliable calculation methods for this technology in structural applications. He is also researching reinforcement methods to achieve sustainable structural objects and constructions.
- **Sylvain Usai** is an architect who develops digital fabrication solutions for complex timber structures at Design-to-Production. He works in collaboration with architects, engineers and contractors to precisely describe free form buildings using custom-made software programmes for realisation. Usai gathered experience in programming and design for manufacture and assembly while working on free form projects such as La Seine Musicale in Paris (2015-2017), and the Swatch Headquarters in Biel (2017-2019), as well as standard projects such as Krokodil Lokstadt Winterthur (2019).
- **Hasti Valipour Goudarzi** is a designer and digital fabrication research assistant at the Center for Information Technology and Architecture (CITA) at the Royal Danish Academy, Copenhagen. She specialises in robotic fabrication with an emphasis on additive manufacturing (AM) for bio-based materials. She co-taught at École Spéciale d'Architecture (ESA) in Paris and conducted workshops focused on digital design and fabrication in Tehran. She has co-organised three exhibitions concentrating on robotics and digital fabrication, the latest being for the Tehran Biennale.
- **Dr Tom Van Mele** is co-director and head of research at the Block Research Group (BRG), ETH Zürich, and lead developer of COMPAS, an open-source computational framework for research and collaboration in architecture, engineering, and construction. He joined the BRG in 2010 and was appointed Senior Scientist at ETH in 2018. His technical and computational developments form the backbone of multiple flagship projects, including the Armadillo Vault (2016), Striatus Bridge (2021), NEST HiLo unit (2021), Phoenix Bridge (2023), and the Rippmann Floor System (2023).
- **Dr Lauren Vasey** has been a postdoctoral researcher at ETH Zürich and within the National Centre of Competence in Research (NCCR) Digital Fabrication since 2020. Her research focuses on adaptive full-scale robotic construction methods. From 2014-20, she was a research associate at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart, where she received her doctorate and taught in the Integrative Technologies and Architectural Design Research (ITECH) programme.
- **Emmanuel Vercruysse** is a designer with a deep interest in the relationship between drawing and making. He approaches design as a tacit process, and as a series of translations between drawings and objects that oscillate between intuitive acts and precise operations. This approach to design combined with his in-depth knowledge of digital fabrication techniques means that he continues to explore the production of architecture intuitively through iterations of drawing, craft, intuition, and code. He is Co-Director of the Design + Make course and Head of Physical Production and Academic Resources Hooke Park, at the Architectural Association.
- **Hans Jakob Wagner** is leading the Computational Wood Architecture research group within the Institute for Computational Design and Construction (ICD) at the University of Stuttgart. His research interest revolves around the question of how computational design, advanced wood building systems, and robotic fabrication processes can enable a ubiquitous shift towards high-quality timber structures in the built environment. He is also founder and director of Corthus - a specialised consulting firm within the timber construction industry.
- **Anne-Kristin Wagner** is an architect who researches and teaches in the field of sustainable buildings. Her research focuses on reuse strategies and life cycle assessments of materials and buildings. She has a strong interest in sustainability strategies for the building sector and at neighbourhood level to mitigate the ecological footprint. She is a research associate and PhD student in the Department of Design and Sustainable Building (Entwerfen und Nachhaltiges Bauen, ENB) at the Technical University of Darmstadt.
- **Blaise Waligun** is a structural engineer and project consultant with Simpson Gumpertz & Heger (SGH), in Boston, Massachusetts. His work focuses on sustainability, specialty structures, experience-based design, and architectural structural systems, where the structural system represents a vital part of and is integrated into the art or architectural design. Waligun holds a Bachelor's and Master of Architectural Engineering from Pennsylvania State University.
- **Ming-Yang Wang** is a researcher and designer focused on computational design and robotic fabrication. At present, he is a doctoral researcher in the Chair of Digital Building Technologies, Institute of Technology in Architecture, ETH Zürich. His research centres around on-site concrete construction, particularly emphasising monolithic techniques as part of the broader Swiss National Centre of Competence in Research (NCCR) Digital Fabrication (DFAB) initiative.
- **Timothy Wangler** is a senior researcher in the Chair of Physical Chemistry of Building Materials at ETH Zürich, with primary research interests in materials science and chemical engineering of construction materials, particularly digital construction with concrete and sustainability.
- **Jessica Watts** is a chartered engineer with ten years experience across building physics, façades/structural design, and sustainability. She has completed various life cycle assessments (LCAs) including base buildings, fit-outs, and products, for both certifications and design development. In addition to being a senior sustainability consultant at Arup, Jessica has contributed to academia in the LCA field as a tutor for master's students at the University of Sydney and a learning facilitator for the Massachusetts Institute of Technology (MIT) Professional Education LCA course.
- **Dylan Wood** is an assistant professor at the University of Oregon's Department of Architecture and Environment, where he leads the Material Intelligence Lab. Previously, he led the Material Programming research group at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart, where his team developed computational design and manufacturing principles for utilising and functionalising naturally smart materials. His work has been implemented across scales, ranging from responsive wearables to passive weather responsive façades and large scale self-shaping timber building components.
- **Thomas Wortmann** is a tenure-track professor and director of the Chair of Computing in Architecture at the Institute for Computational Design and Construction (ICD), University of Stuttgart. Before joining ICD, Wortmann taught at the National University of Singapore and held a position at Xi'an Jiaotong-Liverpool University in Suzhou, China. He researches the use of computational methods such as optimisation, multi-variate visualisation, and machine learning in architectural design processes, and leads the development of Opossum, a machine-learning based optimisation tool.
- **Dr Jan Wurm** is Professor for Regenerative Design at the Department of Architecture at KU Leuven and is Venturing Lead for Arup in Europe. He obtained a Diploma of Architecture at RWTH Aachen in 1999, followed by a PhD at the Faculty of Architecture in 2005. As a director of Arup, Wurm has been leading Foresight, Research and Innovation and Arup's Material Skills Network in Europe. Recognised internationally as an expert for sustainable materials and building systems, he has steered award-winning applied research projects. At KUL he is establishing a research programme for biofabrication and bioconstruction.
- **Xiliu Yang** is a research associate at the Institute for Computational Design and Construction and the Cluster of Excellence (IntCDC) at the University of Stuttgart. Her research interests include the design of human-centered systems and interfaces that bridge automated, robotic fabrication and manual, skill-driven processes. She is at present working on head-mounted augmented reality applications for human-robot collaboration in the timber prefabrication environment.
- **Dr Fahimeh Yavartanoo** holds the position of Research Assistant Professor in the Architectural Engineering Department at Seoul National University of Science and Technology, Seoul, Korea. Since gaining her PhD from Seoul National University in 2021 she worked as a postdoctoral researcher for its Department of Landscape Architecture for two years. Her current research focuses on preserving and retrofitting concrete and masonry structures and designing and analysing complex systems susceptible to earthquakes and wind loads.
- **Jack Young** is an English computational designer who seamlessly integrates craft and expressive material behaviour with cutting-edge digital design tools. Armed with a master's degree in architecture, he specializes in the intricate design and fabrication of complex geometries, pushing the boundaries of innovation in his field.
- **Erik Zanetti** is a research associate at the Professorship for Digital Design and Fabrication (DDF) at the Karlsruhe Institute of Technology (KIT), where he conducts research into circular construction, leveraging computational design and digital fabrication methodologies. His primary interest involves exploring digital tools to unlock innovative material applications and construction strategies. Before taking on his current position, he worked as a computational designer, digital fabrication specialist, and lecturer.
- **Mehrdad Zareian** is a research associate at the Professorship for Digital Design and Fabrication (DDF), University of Stuttgart. His role in the group is related to robotics and automation. Previously, he worked as a research assistant at Max Planck Institute for Software Systems (MPI-SWS) in Kaiserslautern, where he focused on formal methods in control. His research interests lie in theoretical areas, such as formal methods in control systems, and applied control, such as path planning and robotics in architecture.
- **Christoph Zechmeister** is an architect, researcher, and computational designer. His research focuses on developing methods and processes for the design and fabrication of large-scale fibre composite structures spanning a diverse array of material systems. He has worked in several architecture offices including Baumschlager Eberle and UNStudio. At the University of Stuttgart's Institute for Computational Design and Construction (ICD), Zechmeister leads the Computational Fibre Architecture Research Group, working on developing and deploying methods of design and fabrication of large-scale fibrous building systems.
- **Dr Hikmat Zerbe** is the head of Structural Engineering at CIVE, a Houston-based design-build firm serving a wide range of industries. His professional life spans more than 35 years in the computer modelling, analysis, and design of all types of structures with diverse full-time and part-time teaching positions. Zerbe is at present focusing on all 3D concrete printing aspects as he foresees the great rewards it can bring to the construction industry in the future.
- **Meng Zhang** is a professor at Northumbria University. She is at present co-lead of the Living Construction research group within Hub for Biotechnology in the Built Environment (HBBE). Her research focuses on applying microbial biotechnology to the built environment, particularly in living construction, which aims to develop design methods and processes that embrace the complexities of biological systems and digital fabrication. The key to her research is seeing growth as a manufacturing process, producing materials properties that are enhanced as a result of the use of these biological systems through sensing the responsiveness of living cells.
- **Yefan Zhi** is a PhD fellow in the Department of Architecture at the Weitzman School of Design, University of Pennsylvania. His research centres on the energy and material efficiency of architectural structures. Extensively exploiting graph theory and computational geometry, he is at present working on materialising and optimising architectural-scale robotic additive manufacturing.
- **Sasa Zivkovic** is an assistant professor and the BArch programme director at Cornell University AAP, where he directs the Robotic Construction Laboratory (RCL). He is also a co-principal of HANNAH, an experimental and award-winning architecture practice based in Ithaca, NY. HANNAH and RCL explore the implementation of construction techniques such as additive concrete manufacturing and robotic wood construction at full scale. Zivkovic's work and academic research have been widely published in book chapters, journals, and at peer-reviewed conferences.
- **Max Zorn** is a research associate at the Institute for Computational Design (ICD) at the University of Stuttgart. Prior to joining ICD, Max gained professional experience in simulating and analysing building performance at the Chair of Building Technology and Climate Responsive Design, TUM, and at Transsolar. His research focuses on interactive, multivariate visualisation tools for design space exploration. Zorn leads the developer team of the optimisation plug-in Opossum and was involved in the development of the agent-based modelling plug-in ABxM.

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FABRICATE 2024: 'CREATING RESOURCEFUL FUTURES' IS THE FIFTH VOLUME IN THE SERIES OF FABRICATE PUBLICATIONS. THE FIRST CONFERENCE – 'MAKING DIGITAL ARCHITECTURE' – EXPLORED THE WAYS IN WHICH TECHNOLOGY, DESIGN, AND INDUSTRY ARE SHAPING THE WORLD AROUND US. SINCE THEN WE HAVE BECOME FINELY ATTUNED TO THE NEGATIVE IMPACTS OF THIS SHAPING. THE 2024 CONFERENCE, HOSTED IN COPENHAGEN, SETS FOCUS ON THE PRESSING NEED TO DEVELOP NEW MODELS FOR ARCHITECTURAL PRODUCTION THAT RETHINK HOW RESOURCE IS DEPLOYED, ITS INTENSITY, ITS SOCIO-ECOLOGICAL ORIGINS AND SENSITIVITY TO ENVIRONMENT. THIS BOOK FEATURES THE WORK OF DESIGNERS, ENGINEERS, AND MAKERS OPERATING WITHIN THE BUILT ENVIRONMENT. IT DOCUMENTS DISRUPTIVE APPROACHES THAT RECONSIDER HOW FABRICATION CAN BE LEVERAGED TO ADDRESS OUR COLLECTIVE AND ENTANGLED CHALLENGES OF RESOURCE SCARCITY, CLIMATE EMERGENCY, AND BURGEONING DEMAND. EXPLORING CASE STUDIES OF COMPLETED BUILDINGS AND WORKS-IN-PROGRESS, TOGETHER WITH INTERVIEWS WITH LEADING THINKERS, THIS EDITION OF FABRICATE OFFERS A PLURALITY OF TANGIBLE MODELS FOR DESIGN AND PRODUCTION THAT SET A CREATIVE AND RESPONSIBLE COURSE TOWARDS RESOURCEFUL FUTURES. UCL PRESS PRESENTS FABRICATE 2024 IN CO-OPERATION WITH RIVERSIDE ARCHITECTURAL PRESS.

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