Bridging The Gap Between Academia and Practice

A case study for collaborative digital design to fabrication workflow for interlocking kit-of-parts

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The implementation of digital design workflows is an opportunity to facilitate the knowledge exchange between the industry and research, required in the face of the climate emergency. This paper presents outcomes of a series of digital design to fabrication workshops, resulting in three-party collaboration between an international architectural design firm, a university, and a global food producer. The paper presents an initial step towards an integrated material system based on an abundantly available industrial by-product of sugar manufacturing. The idea of topological interlocking has been used as a concept to define components-based system for the novel material, tested in a scaled prototype with university students.

Keywords: *Sustainable Digital to Fabrication Workflows, Research in Practice, Industrial Partnership, Topological Interlocking*

INTRODUCTION

With a focus on immediate means of project delivery, architectural practices tend to skew away from emerging knowledge, produced by academia, in favour of established practices. Likewise, practice-led approach could substantially benefit academic research according to Suoranta, Aura and Katainen (2002). This paper presents a step towards an iterative framework for academia-practice research collaboration.

Background

Grimshaw Architects has fostered construction innovation since its establishment in 1980 by Sir Nicholas Grimshaw. Engaging with academia has been recognised by Grimshaw as an opportunity to expand its design capabilities further. Therefore, the practice used the workshops as a tool to investigate sustainable construction systems, utilising several universities' knowledge bases. Moreover, the architects engaged in hands-on prototyping benefited from embodied learning (Zandavali et al. 2020).

Led by the personal initiative of a small group of architects and design specialists, the aim was:

- To explore architectural geometry, material systems and novel fabrication techniques.
- To deliver practical solutions for future architectural projects.
- To create a knowledge-based community in material experimentation across the practice.

Profile of Grimshaw as a practice

Grimshaw delivers high-quality architecture though implementation of novel material systems and ways of construction, demonstrated through projects such as Eden and Waterloo Station.

Design Technology within Grimshaw

Since 2012, the practice has established a Design Technology department to research in BIM, computational design, extended reality (XR), environmental analysis, urban computation, and tool development. The Department works as a separate entity, with specialists embedded within individual design teams. As such, the department faces certain challenges:

- Integration of research in practice
- Knowledge transfer between architects and specialists' staff
- Lack of research continuity over time.

The aim of the research was to enable material systems to be used in the future design projects, providing research integration in practice.

Grimshaw research focus: DfMA, kit of parts.

Grimshaw as a practice has a particular focus to develop designs following Design for Manufacturing and Assembly and kit-of parts approaches to as low-waste, time-effective and cost-efficient practices. Additionally, Grimshaw is constantly looking to reduce carbon footprint (Net Zero Carbon commitment, Grimshaw 2023). The practice focuses on improving the logistic chains and constructability of their designs.

Reasons for Topological interlocking research

Topological interlocking method, with its rich history of use with sustainable materials (stone, timber), offers large spans covered with small members and a high resilience to impact (Weizmann et al. 2015, Estrin, at al. 2011). Topological interlocking systems enable efficient handling and transportation of discrete components to the site, while their mortarless nature enables the system to be easily dismantled and recycled (Tessmann 2012). Therefore, topological interlocking offered a perfect case for a material system to be researched by Grimshaw.

Reference frameworks: other practices

To outline the potential benefits of a tri-fold collaboration between practice, academia, and craftsmen, and in order for Grimshaw to achieve a goal of designing and testing a sustainable construction system, four case studies were identified. Two criteria were used: significant contribution of each of three stakeholder groups to the applied innovation, and an operational built project as a result (Table 1).

As such, the use of stone and cork as a load-bearing material in The Flat Vault (AAU Anastas Website n.d.), Cork House (Wilton, O. and Barnett M.H. (2020) and 15 Clerkenwell Close (Groupwork Website 2017.), reduced carbon emissions, while enabling simple supply chain. Similarly, in Chrystal Houses (Oikonomopoulou, F et al. 2018), the implementation of material and fabrication innovation enabled context integration.

Although it is not always possible to quantify design innovation in numerical values, the comparison outlines the intrinsic value of a collaborative research to ensure successful practical implementation.

Project	Design innovation	Fabrication innovation	Material innovation
Cork House, M.B.H	Unique sustainable housing typology	Robotic milling, calculation of cork as structural material	Use of cork at volumetric depth
Chrystal Houses MVRDV	Historic/ contemporary narrative negotiation	Bespoke methods of glass bricks and window frames.	Use of structural glass in form of bricks
The Flat Vault AAU Anastas	Traditional local material language reinvented	Discrete systems engineering, robotic stone cutting	Use of structural stone for spanning structures
Clerkenwell Close Groupwork	Narrative of bare material expression	Carbon calculation for stone loading, testing	Use of structural stone for multistorey building

Table 1
Reference Practice-Academia-Manufacturer collaborations

FRAMEWORK AND TIMELINES

The following chapters describe five consecutive workshops (2018-2022), spanning architectural geometry, sustainable materials, and robotic fabrication (see Figure 1).

In 2018, during Advances in Architectural Geometry (AAG), the research topics were put forward: interlocking systems, sustainable materials, and subtractive robotic fabrication. Returning to AAG in 2020/2021, the team refined the interlocking geometry research, followed by a workshop with UCL Bartlett to address technical aspects of hot wire cutting.

At this point, the team narrowed down to a specific case of topological interlocking, due to the system's constructability benefits (see Reasons for Topological interlocking research).

In 2022, the team engaged in a three-fold collaboration involving Grimshaw, University of East London, and a Tate and Lyle Sugars, resulting in the development of a sustainable interlocking slab system – Sugarcrete® Slab. The events are described in detail in the following chapters.

PHASE I: GEOMETRY EXPLORATION

In the Phase I (2018-2021), the team focused on the geometrical exploration of the interlocking designs, as well as the means of fabricating them in a nominal material, Styrofoam (Figure 2).

Through two consecutive workshops at AAG 2018 in Chalmers University of Technology; Gothenburg, Sweden and 2020/2021 in Ecole des Ponts ParisTech, Paris, France, the methodology for creating topological interlocking designs was tested with the groups of students of 8-10 people. The workshops engaged a design to fabrication pipeline (Shilova, E. et al. 2018), and method by (Estrin, Y at al. 2011) to create a model of an interlocking shell segment with a ruled interfaces (in 2018) and straight interfaces (2020).

In 2018, participants designs were primarily modelled manually using Rhino 3D. The manually modelled geometries resulted in high (up to 75%) failure rate due to incorrect interlocking alignment or gridlock assemblies which could not be taken apart. Therefore, to ensure the viability of interlocking designs proposed by students, the following were developed:

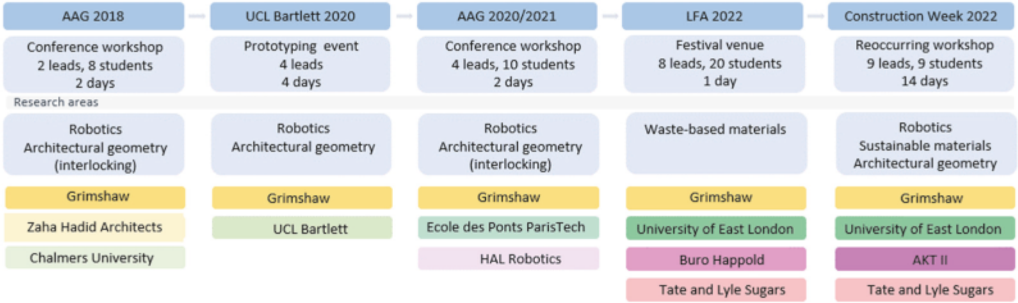
- A rule-based interlocking guide.
- A framework for automated process for generating 3d assembly from 2d line sketches

Geometry generation framework

The developed framework, subsequently used for later workshops, used an iterative workflow.

First, the students drew a 2d patterns in Rhino (Figure 5b) using a specified set of rules. Then, the students identified a repeated 'tile' and drew a pattern network diagram in Rhino (Figure 3a).

Each curve represented a discrete element in plan and was put on a separate-colored layer. The curves were then inputted into an automated script, which recognized each curve as a block and joined same-colored opened curves on the edge of the tile (Figure 3b).



AAG 2018	UCL Bartlett 2020	AAG 2020/2021	LFA 2022	Construction Week 2022
Conference workshop 2 leads, 8 students 2 days	Prototyping event 4 leads 4 days	Conference workshop 4 leads, 10 students 2 days	Festival venue 8 leads, 20 students 1 day	Reoccurring workshop 9 leads, 9 students 14 days
Research areas				
Robotics Architectural geometry (interlocking)	Robotics Architectural geometry	Robotics Architectural geometry (interlocking)	Waste-based materials	Robotics Sustainable materials Architectural geometry
Grimshaw	Grimshaw	Grimshaw	Grimshaw	Grimshaw
Zaha Hadid Architects	UCL Bartlett	Ecole des Ponts ParisTech	University of East London	University of East London
Chalmers University		HAL Robotics	Buro Happold	AKT II
			Tate and Lyle Sugars	Tate and Lyle Sugars

Figure 1
Events timeline, setup, research areas and key stakeholders

The volumetric discrete components were first generated in small test batch, following method of Estrin, Y at al. (2011) (Figure 3c). If the script resulted in invalid geometry, students modified the 2d pattern until valid geometry was generated. The script populated a curved shell segment with the resultant 3d blocks (Figure 3d).

Students experimented with the following parameters: size of components, depth, incline of interfaces, and interface curvature (Figure 10, b1,2). The designs were not assessed on notions of materials and constructability at this point.

Selected digital designs were then cut in EPS Styrofoam; and a custom set of scripts using Grasshopper, Python and C# was developed, connecting geometry generation process with the cutting toolpath script for the 6-axis robotic arm.

Additionally, to refine robotic hot wire cutting technical details, Grimshaw and The UCL Bartlett B-made arranged a third workshop, testing a 1:10 model of a roof bay for an infrastructure project. Hot wire cutting with 6-axis robot arm defined parameters of 100mm/s linear speed and 1.5 mm wire (with 15 kg/m3 EPS) to achieve a maximum tolerance of -4mm. These parameters were used in subsequent workshops.

Covid-19 remote setup:

The AAG 2020 workshop, originally planned in person in 2020, happened in 2021 during lockdown in a hybrid mode. Participants from Greece, Egypt, UK, Germany and Australia joined the workshop remotely. The workshop leaders in London presented remotely, while workshop leaders in France were cutting components by robotic arm in real time. A live stream from the robot cell could be accessed by students at any time to observe and ask questions about the tool calibration, cutting and assembly.

Interlocking designs variation.

Evolution of interlocking designs (Figure 4) shows a range of non-specific patterns with identical components in 2018 (A1-A4), complex digitally generated designs with variation of blocks within one pattern (B1-B2), and notions of material sensibility in 2022 (C1-C2, see Phase II).

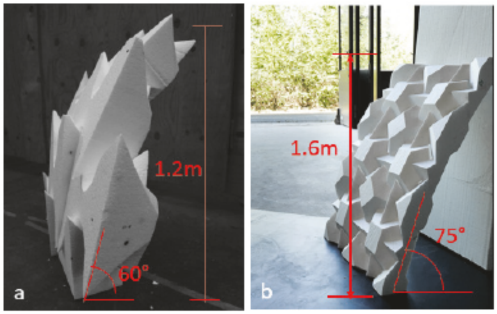


Figure 2
Prototypes of segmented shells at AAG in 2018 (a) and 2020/2021 (b)

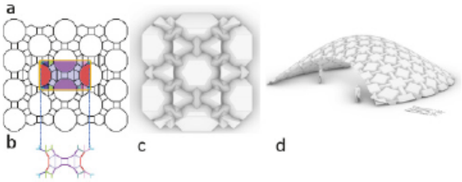


Figure 3:
Interlocking digital generation workflow.

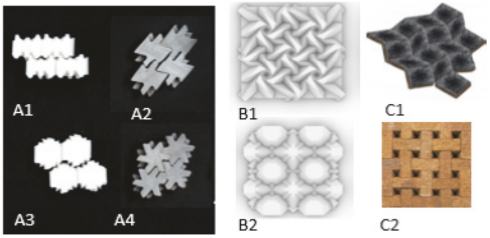


Figure 4:
Interlocking design evolution: AAG 2018 (A1-4), AAG 2020/2021 (B1-2); CW 2022 (C1-2)

PHASE II: MATERIAL INTEGRATION

In the Phase II, the team developed material strategies, suitable for the application with the previously developed interlocking geometries.

London Festival of Architecture (2022)

In 2022, Grimshaw and University of East London (UEL) organized a one-day workshop for London Festival of Architecture (LFA). The team used this event as an opportunity to develop a material suitable for the interlocking systems from the previous workshops (Figure 5, Table 2).

Input from prior research:
- Topological Interlocking research, Abeille design
- Material: Prior research of sugarcane bagasse formulas

Learning output:
- Material formula with improved compressive strength
- A full-scale tetrahedral block in sugarcane material

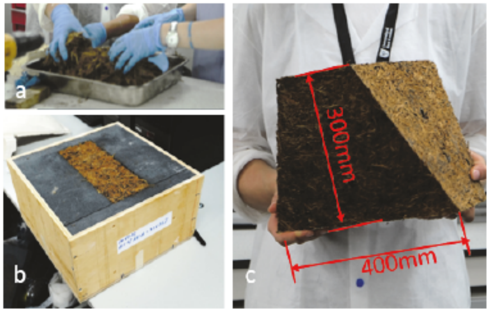


Figure 5
LFA 2022
Research inputs (above); material hand mixing (a), mold (b), unmolded block(c)

Table 2
LFA 2022
information

Addressed research agendas:	
Robotic Fabrication (prior)	no
Interlocking design (prior research)	no
Sustainable material	yes
Tools:	
6-axis robotic arm (molds insert in dense foam)	
Degree of students' input	
Design of main prototype (block)	no input
Design of the material mix	some input
Fabrication (Casting)	students

Prior to LFA engagement in 2021, UEL developed a novel sustainable material made of a sugar manufacturing fibrous by-product– *bagasse*, using quick lime and water as a binder. However, the material had very little (0.5MPA) compressive strength and did not allow for application in an interlocking system of a slab (selected as a test loading condition).

Laboratory experiments were conducted to bring the material compressive strength to sufficient rate (5MPa), and Sodium Silicate was used as a binder to create a sustainable material with improved structural performance.

The workshop's aim was to test casting of developed bagasse-based material into reusable molds by hand (Figure 6a-b) to achieve truncated tetrahedral blocks (Figure 6c), following 1699 patent of interlocking Abeille Flat Vault (Brocato and Mondardini 2012).

Participants included members of the public, students and workshop leads from Grimshaw and UEL. Simple material mix and the ease of casting enabled first-hand, intimate experience of this novel material to the participants.

LFA workshop impact

The event has acted as an idea catalyst for future material research, generating discussions around sustainable materials and cutting-edge construction systems.

Most importantly, the workshop included attendees from the local neighbourhoods, different backgrounds and ethnicities, aiming to bring the research to less favoured communities. The workshop prioritised a hands-on material approach, minimising learning barriers for participants without a prior design background.

Developed novel bagasse-based material has been secured under Trademark "Sugarcrete®" (Sugarcrete® trademark 2023), and later used with interlocking Sugarcrete® Slab.

Sugarcrete® use for interlocking systems

The topological interlocking, derived from *stereotomy* (science of cutting three-dimensional solids) has been used historically with solid materials (ie. stone) and subtractive techniques (Weizmann, M., Amir,O., and Grobman, J. 2015).

The novel use of Sugarcrete® for topological interlocking design at LFA introduced additional constraints, related to the use of an additive technique of casting.

Sugarcrete® in its raw form is a fibrous thick paste, which needs to be laid into the mould in batches and lightly compacted by hand (Figure 5 a). Thus, the moulds are required to have at least one flat surface sufficient to access the inside of the mould and compact the material within it (Figure 5b). Moulds are to be covered with release agent

(Vaseline). After compaction, the mould needs to be covered and put under pressure weight, to maintain compaction.

After the casting, the block requires 2-3 days in the mould for the binder to penetrate the fibres. After demoulding the block needs to dry at 25-45 °C for 10-14 days; and the mould can be reused. The moulds included a wooden plywood box and four interchangeable inserts out of dense foam; designed to be easily taken apart and reused (Figure 5b). Please refer to Sugarcrete® - Video (2023) for the recording of the process.

Lastly, small details and sharp (<60 degrees) angles within the design of the block were avoided in designs of Sugarcrete®· blocks as sharp corners could break during demoulding.

CONSTRUCTION WEEK (2022)

UEL Construction Week is an annual two-week event aiming to provide the students with the hands-on experience in novel fabrication systems. The students are encouraged to use hand tools, CNC and a 6-axis robotic arm to learn through making. Grimshaw was invited to lead a workshop in 2022, to showcase the value of digital fabrication in real-world construction.

The workshop incorporated material testing, parametric design, assisted assembly with augmented reality and robotic cutting (Table 3). The inputs were derived from prior research: material (Sugarcrete®), fabrication (casting), as well as the digital to fabrication toolchain.

The main prototype design (Figure 6), based on 1699 Abeille Flat Vault was prepared by workshop leaders in advance.

The following were designed by the students:

- Digital design of an interlocking material system in response to a geographic and social context. The students were encouraged to adapt their design briefs to the local constrains and challenges of real sugarcane plantation communities.
- Assembly strategy for the final prototype.

Input from prior research:
- Updated material with improved compressive strength
- A digital tool to create 3-dimensional TA from patterns

Learning output:
- Conceptual prototype of a floor slab, material limitations
- Workflows to use Sugarcrete^{TM} for interlocking designs.
- Practice, university and industry collaboration framework

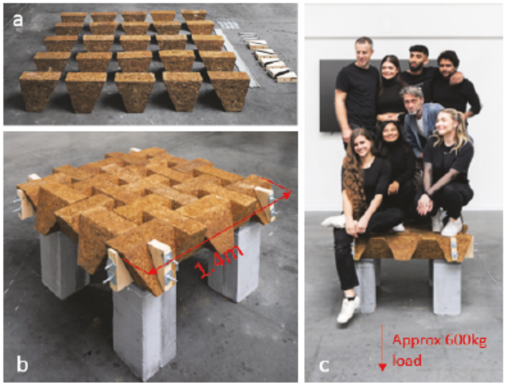


Figure 6
Construction Week Research inputs (above); Kit of parts pre-assembly arrangement (a); assembled prototype (b); experimental loading (c)

Table 3
Construction Week information

day	Degree of students' input: Week 1	
1	Material system design	students
2	Teams interlocking designs	students
	Interlocking digital tool dev.	no input
3	Robotic toolpaths simulations	students
4	AR-assisted assembly	some input
	Degree of students' input: Week 2	
-	Blocks casting (prior)	no input
5-8	Assembly sequence design	students
9	Assembly, Structural testing	students
10	Documentation of workshop	students

Addressed research agendas:	
Robotic Fabrication	yes
Interlocking design research	yes
Sustainable material	yes
Tools:	
6-axis robotic arm;	
3d printer (Ultimaker), 3d Scanner	
Digital: Rhino, Grasshopper, Fologram	

During week 1, students developed desigs in response to chosen local context, using previously developed workflows and several new tools.

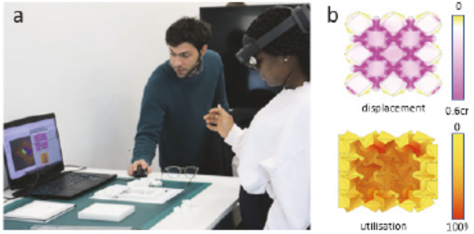


Figure 7
Digital design assessment tools: AR-assisted assembly (a); structural analysis (b)

Digital design assessment tools

The previously developed interlocking digital toolkit enabled an infinite number of complex designs without the ability to critically appraise them. For the Construction Week, several digital design validation tools were added to the toolkit.

AR assisted assembly

An augmented reality (AR) -assisted assembly tool was developed to create the learning design-assembly feedback loop (Figure 7). The assembly simulation used 15x20cm 3d printed models of students' designs. The task was to arrange loose components of the 3d pattern within the fixed boundary, aided by AR overlay. Three devices had different setups: two tablets with a bespoke AR application showcasing the assembly sequence, a custom Fologram application for mobile and VR headsets allowing users to interact with individual pieces and validate their design (Figure 7, Figure 8c-d).

First, the boundary frames were placed on to QR codes. Devices tracked the QR codes and created hologram overlays. The students used holograms as a guide to infill the frames with loose blocks, iteratively changing assembly sequence using a Grasshopper definition.

Carbon footprint analysis tool

The carbon footprint tool provided instant feedback on the amount of embedded carbon for students' designs. The tool estimated the carbon footprint given a single block volume, number of blocks in a m^2, and carbon footprint for m^3 of the material mix (using data from Bath University's Inventory of Carbon and Energy (ICE).

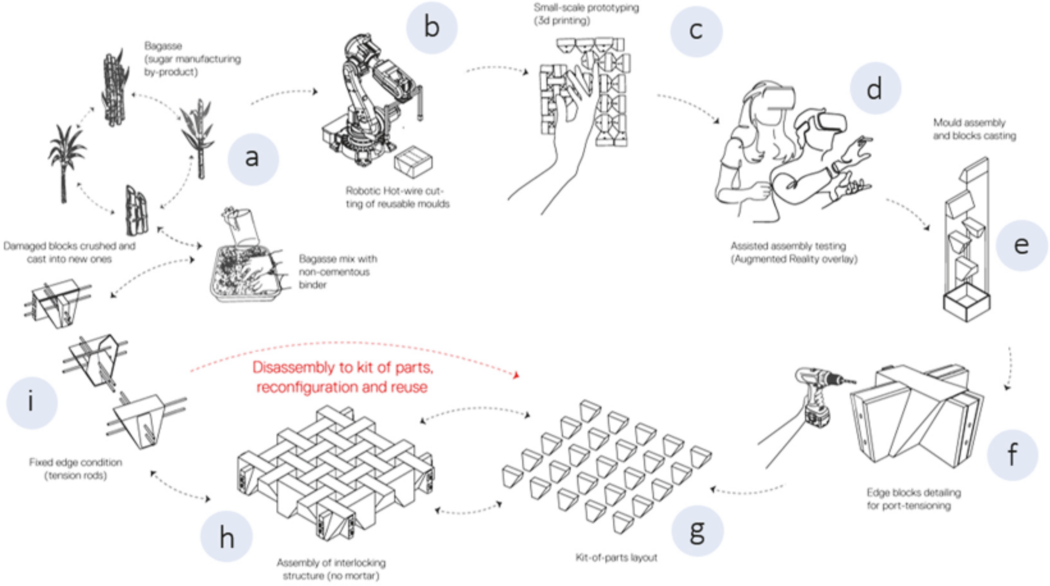


Figure 8
Construction Week workflow: Bagasse mix (a); Robotic cutting(b); Scaled prototypes (c); AR-assisted assembly (d), molds assembly (e); Pre-drilling of edge blocks (f); kit-of parts layout on the ground (g); prototype assembly (h); tensioning (i)

Structural analysis tool

A structural assessment tool was developed using Karamba (Figure 7b) to help the students validate their designs. The tool used 3d design, and material properties to provide an average deflection under a case study load.

Resulting students' design proposals

A range of proposals was developed by the students, spanning temporary habitation, retrofitting and water management (Table 4).

Table 4
Student proposals in response to a local context

Team Brazil	Modular kit-of parts prefabricated houses for favelas (Figure 9c)
Team Australia	Fireproof cladding for existing buildings (retrofitting) (Figure 9b)
Team India	Temporary shelters for female sugar cane harvesters, air permeable skin
Team Thailand	Recreational canopy with water collection function (Figure 9a)
	Air purification cladding system utilising charring (Figure 9d)

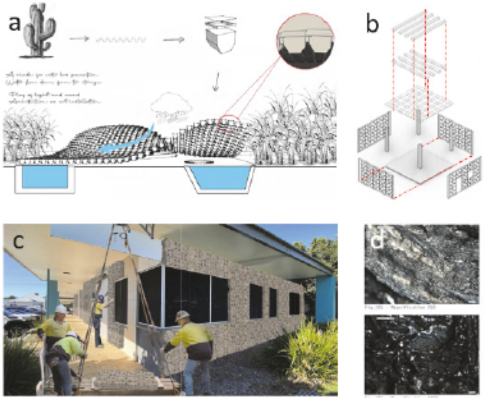


Figure 9
Students' proposals visualisations

Sugarcrete® Slab prototype

During week 2, students assembled a 1.4x1.4 m interlocking slab prototype (Figure 7). Material compressive strength (5MPa) determined the 300mm slab depth. 25 identical tetrahedral blocks were cast in advance due to the curing time.

The students' task was to assemble a slab structure without binder (Figure 6b), tensioning the boundary blocks with steel threaded rods (Figure 7h). Students also developed a pre-assembly layout (Figure 6a), and jig for hand-drilling of edge blocks (Figure 7f).

The prototype was empirically tested with 7-person load (Figure 6c) and 3d scanned, revealing -43mm deviation in length from the digital model, possibly due to material shrinkage.

Engineering considerations.

The added benefits of post-tensioning were not considered at this stage, and once tightened, the system was considered to act like a continuous slab. Required reinforcement (dia. 10mm) at perimeter was calculated based on the material compressive strength. A nominal tension was based on the amount of extra compressive capacity in blocks after considering the compression already in the system when loaded (up to 3m span). A maximum torque for tightening the ends of the rods was then calculated as number of turns of the cap nuts.

Lessons learned.

Several technical successes have been identified through the presented case studies:

- Novel use of a topological interlocking designs with the by-product-based material.
- Incorporation of 'no-waste' approach though use of casting and reusable moulds.
- A complete design to production workflow.

Several limitations have been observed:

- The material capabilities limit span of the slab to approx. 3m between the supports.
- The material resolution of Sugarcrete® in interlocking assemblies does not allow for sharp edges (< 60 °) and fine details.
- Size imperfection of individual blocks due to manual production and shrinkage resulted in a considerable tolerance (-43mm) across multi-component dry assembly.

DISCUSSION.

Learnings from collaborative work.

The research in practice often happens chaotically, on an ad-hoc basis, for a variety of design briefs and with different parties involved.

For practicing architects, it is challenging to pursue a consistent research agenda long-term, as the opportunities to push the research forward are frequently set apart in time and are not carried out by the same group of people.

This paper presents a case study involving two architectural practices, four universities and two industrial partners: resulting in one integrated material system – Sugarcrete® Slab. The novelty of the research therefore lies not purely in the technical domain, but rather in a collaborative workflow that has been carried through (Figure 10).

Learning to acknowledge the nature of the research in practice and taking the opportunity to put steps forward though separate research occurrences have been key to push the agenda forward.

Several good practices were identified:

- One clear research focus for one event. In case of Sugarcrete® Slab, aspects of geometry (AAG2018 and 2021), technology (UCL Bartlett 2020) and material (LFA 2022) were tackled individually in separate workshops.
- A clear research question for each workshop.
- Treating each workshop as a research experiment, documenting research learning.
- Research transparency. As such, the team decided not to patent the method for the benefit of an architectural community. The scripts comprising the digital toolkit are to be publicly available as a Grasshopper plugin.

Collaborative research impact

The research was nominated for Earshot 2023 prize and was numerously published in the architectural magazines such as Dezeen, ArchDaily and RIBA Journal (Cousins, M. 2023). The prototype was presented to His Majesty King Charles III and exhibited at the Royal Academy of Arts Summer Exhibition in 2023.

Future research

Further research is required to determine feasibility of using Sugarcrete® Slab in construction including scale limitation, tolerances, and alternative reinforcement studies. Further studies are required to integrate the slab with existing structural systems (such as timber frame).

Further material studies are required to quantify the material behaviour (shrinkage, durability, resistance to water and sun exposure, pest control). Standards need to be developed to use the material at industrial scale.

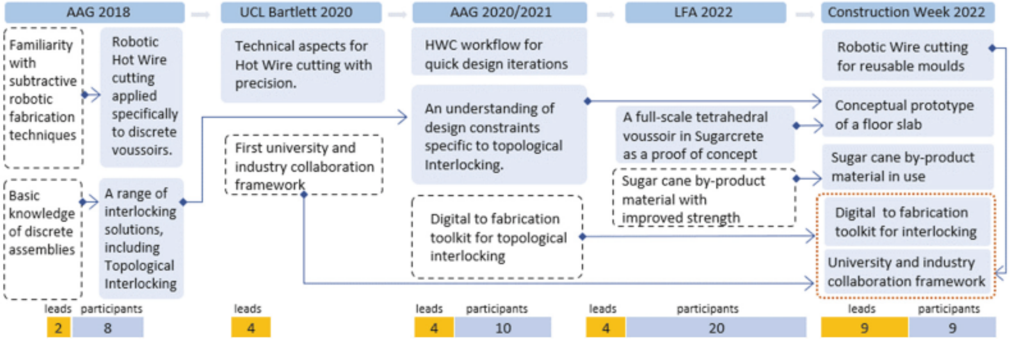


Figure 10
Iterative learning workflow (2018-2022); workshops lead to participant ratio (below)

Further steps to strengthen academia-practice knowledge transfer may include staff exchange between the university and the practice.

CONCLUSION:

This paper presents a case study for iterative in-practice research through workshops, using both digital and hands-on tools. In addition, the paper showcases knowledge transfer mechanisms between academia and practice.

The results show several technical innovations, notably the digital design to fabrication workflow to apply novel Sugarcrete® material to topological interlocking designs. Further research is required to ascertain the value of the material system in full-scale construction.

The methodology offers a variety of pedagogical tools; while iterative approach enables building academia-practice relationships with multiple entities, creating more opportunities for research integration in practice.

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