AM Perspectives

2

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AM Perspectives 2
Research in Advanced Manufacturing
for architecture and construction

AM Perspectives 2 results from a collaboration between the Landscapes, Heritage and Territory Laboratory, University of Minho (Lab2PT); Architecture, Construction and Technology Hub, University of Minho (ACTech Hub); Institute of Structural Mechanics + Design, TU Darmstadt (ISM+D); Generative Design Lab (GDL), TU Darmstadt; Politecnico di Milano, Department of Architecture, Built Environment, and Construction Engineering (DABC); AS|Lab, Politecnico di Milano; Stichting OpenAccess Platforms (SOAP).

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Research in Advanced Manufacturing for architecture *and construction*

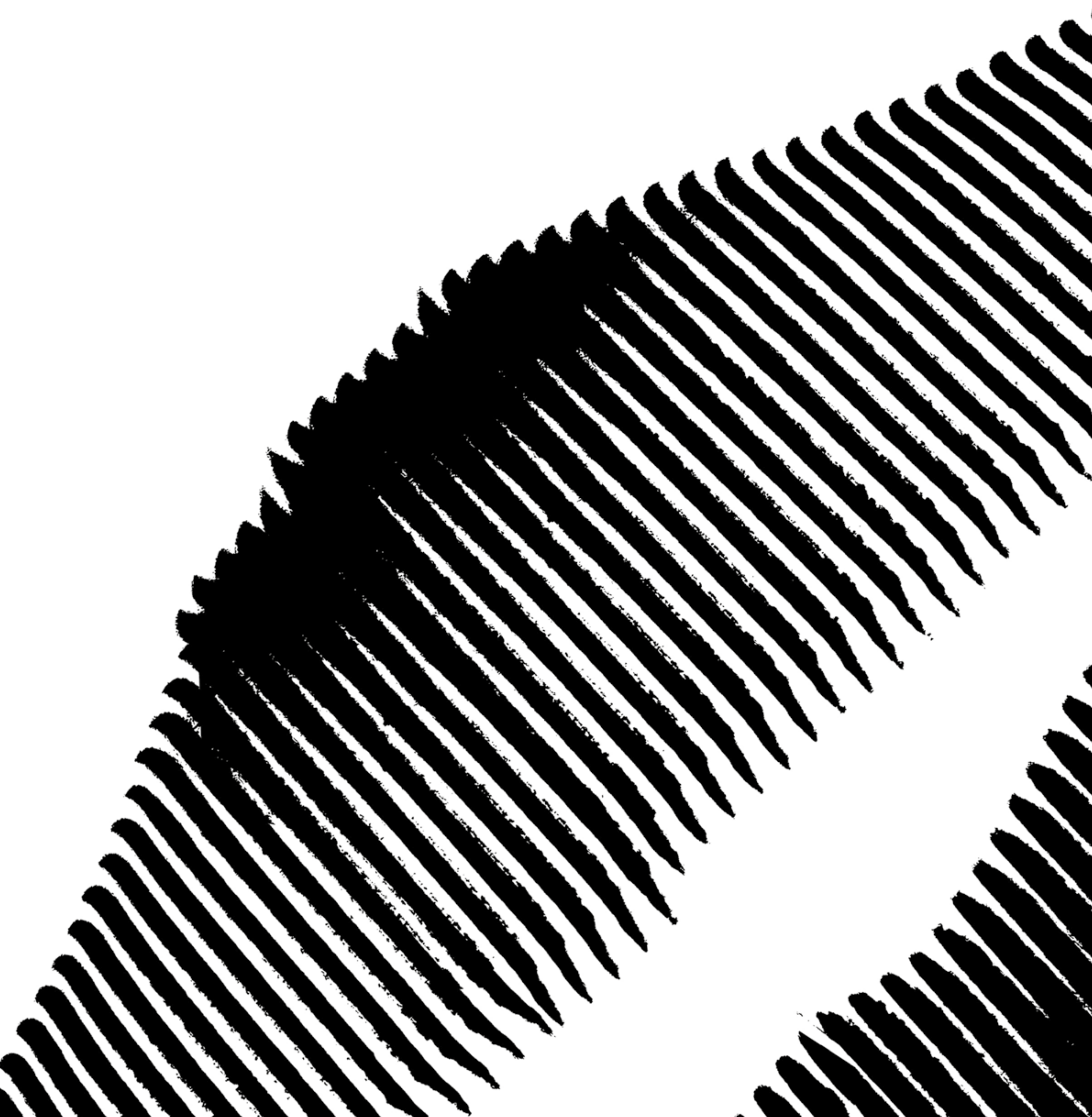
Laboratory of Landscapes,
Heritage and territory

Institute of Structural
Mechanics and Design

Department of Architecture,
Built Environment, and
Construction Engineering

SOAP | Stichting
OpenAccess Platforms

4. *Advancing* Manufacturing



The pressing challenges of climate change, reduction of available material and skilled labor for construction, have given a big input to the development of advanced manufacturing, declined in the triad of additive manufacturing, subtractive manufacturing and robotic platforms.

Additive Manufacturing (AM) has held its promise of mass customization, from the component scale to full building scale, providing the imagination that each component could be tailored to specific needs without significantly affecting its production costs or time. Today we are witnessing, that while, perhaps, complete dwellings have not been additively manufactured, certainly there have been few houses and neighbourhoods, having their walls fully 3D printed. We have seen them, to be developed in a variety of materials, from concrete, having the largest share, to earthen and bio-based now starting to appear. Bringing to the resurge of the traditional materials, as well opening up to a nearly infinite exploitation of innovative materials, which can be tailored to use organic compounds, to achieve thermal, acoustic and structural performance on demand.

The definition, prediction and assessment of the performance of those advanced manufactured materials, components, buildings and infrastructures is enabling to refine AM and the development of new architectural tectonics. Numerical and Virtual simulations are enabling prediction and testing of manufacturing stages, in use performances, and life cycle assessments to measure innovation versus current sustainable development goals.

Lately, we are also witnessing the manifestation of the (once) utopian dream of having machines, and robots around us building up components, and full structures. How far are we from the Plug-in City envisioned by the Archigram or by the Gramazio & Kohler urban forms resulting from robotic logics rather than human hands? Perhaps, we are still quite distant by their complete realization, but robotic agents are becoming real in the construction realm. From robotic systems assembling components, to platforms automating repetitive tasks, to digital twins sensing the cities, and drones constructing in harsh environments, we are witnessing growing human-robotic interactions.

Therefore, this book presents and discusses upon the latest research in the field of advanced manufacturing for the building realm, simulation for the advancement of customized properties of AM components, and robotic manufacturing of construction systems developed across a vivid network of researchers based in European Universities. We hope this book can stimulate reflection about the current and future trends in construction automation, with a strong emphasis on their architectural quality, forms of tectonics, and achievable performances. We hope some or many of these, research-based innovation will soon show their full application in construction industry!

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1. Reaso ning Realm

The promise of Additive Manufacturing (AM) in architecture and construction once opened a realm of seemingly endless potential, with research roadmaps defined to pursue goals of material efficiency, formal freedom, and automation-driven precision [1- 4]. Yet, decades after the initial excitement, this realm remains fragmented, shaped as much by its ambitions as by its constraints, its hype as by its realities [5]. The authors of this chapter portray what was once imagined as a revolutionary new paradigm, but which now appears more as a patchwork of isolated experiments, uncertain trajectories, and unresolved contradictions. We enter this contested territory not to resolve it, but to reason through its tensions.

Reasoning Realm refers precisely to this reflective stance, a careful, grounded interrogation of AM place in the evolving material, technological, and environmental cultures of building, and in its tectonics. This resonates with Suzi Pain's research, which situates AM tectonics within their socio-material contexts, challenging deterministic narratives through a focus on labour, context, and architectural ecologies [6]. It stands as a counterpoint to the enthusiastic propagation of AM, which has so far failed to fulfill its design ambition of responding to contemporary challenges. If advanced manufacturing techniques are to shape the future of architecture, then their motivations, costs, and aesthetics, and criteria of adoption must be examined with clarity, not assumed. This chapter brings together perspectives that, while distinct in tone and approach, converge on a common concern, how to assess AM not just as a technological proposition, but as a cultural, ecological, and architectural project.

What was initially embraced as a tool for unprecedented creativity has too often resulted in crude, monolithic forms that replace the richness of craft with the monotony of extrusion. In his essay, Marcel Bilow invites us to temper our fascination, who warns against the profession uncritical enthusiasm for scaling up a technology often unsuited to architectural complexity. Rather than endorsing AM as a universal solution, he argues for its targeted use, in the fabrication of specialized elements, where conventional methods fall short. In his view, the real failure lies not in the limitations of the machines themselves, but in our tendency to treat them as a symbol of progress rather than a tool with precise, context-specific utility. The gap between technological possibility and architectural intent is, in many cases, expressive. From early prototypes to recent built examples, the majority of 3D printed buildings disappoint, not because the machines failed, but because expectations were misaligned.

It is time to scrutinize the trajectory of AM. Focusing on façade and construction systems, and drawing on over a decade of observation, Holger Strauß maps the persistent dissonance between AM envisioned potential and its limited integration into the building industry. He points to the persistence of conventional assembly logic, even in supposedly advanced 3D printed structures, and to the systemic barriers (legal, procedural, economic) that prevent AM from evolving beyond a niche role. The inertia of the construction industry, coupled with the lack of standardized processes and scalable multi-material systems, means that much of what has been achieved remains isolated and provisional. Without a fundamental rethinking of typological, material, and regulatory frameworks, even in cases where AM is used, such as 3D-printed houses, AM will continue to function more as an experimental outlier than as a transformative force. The issue is not just pace of innovation, but keeping misplaced expectations, AM will remain peripheral.

The environmental implications of AM are brought to the forefront by Nadja Gaudillière-Jami, whose work reframes the sustainability discourse around digital manufacturing. Rather than focusing solely on material efficiency, she proposes a broader analysis on carbon footprint and life-cycle approach that includes the robots and machines themselves, particularly their reliance on critical raw materials and energy-intensive systems. Her examination of impact transfers, where benefits in one metric are offset by burdens in another, exposes the hidden ecological trade-offs that often accompany AM. By proposing tools such as environmental threshold modelling and evaluating production strategies based on both material and system impacts, Gaudillière-Jami outlines a path toward more sustainable applications. A perspective that challenges the notion that AM is inherently more ecological and urges the field to develop more nuanced, data-driven assessments. AM, then, is not inherently sustainable, but demands careful calibration and context-specific application.

Taken together, these three contributions state the urge of a pause, a slowing down. In a discipline where the allure of innovation often races ahead of reflection, Reasoning Realm calls for balance. What do we actually need from these technologies? When is AM the right tool, and when is it not? How do we move beyond experimental showcases and toward integrated, context-responsive applications?

Part of this reasoning must also address how AM reshapes the relation between automation and craft. While some celebrate the disappearance of the hand in favor of precision layering, others caution that removing the human from the loop too soon can result in buildings that are neither adaptable nor reparable. Craft is not merely a nostalgic reference to the past, it is a mode of attention to context, to material behaviour, to site and climate, craft as a way of thinking through making, as Richard Sennett suggests in *The Craftsman* [7], a form of situated knowledge and care for materials. The question, then, is not whether AM should replace craft, but whether it can meaningfully converse with it [8].Can automation support circularity, not only through reduced waste, but through design for disassembly, modular reconfiguration, and material traceability? Can printed components be reintegrated into new cycles of use, or are they destined to become new forms of architectural waste?

The construction industry today faces profound challenges. Environmental urgency, social demand for affordable and adaptable housing, the need to decarbonize both materials and methods, these are not speculative questions. In this context, AM and automation cannot be justified on formal grounds alone. Nor can it be deployed uncritically under the banner of productivity. It must prove itself in relation to a broader value system: one that includes ecological accountability, social relevance, technical robustness, and design integrity. Innovation is not neutral. It is always mediated, by the systems we inherit, the values we choose, and the futures we imagine. AM and Advanced Manufacturing can support new, or repurposed construction paths, but only if it is embedded in a meaningful project. That project is not about machines replacing builders, or code replacing detail. It is about finding the right scale, the right scope, the right *fit* between intention and execution. Between digital tooling and the messy realities of site, climate, labor, and use.

Reasoning Realm thus does not offer conclusions. It opens questions. It invites architects, engineers, builders, and researchers to ask not only what AM and Automation can do, but what it should do, and under what conditions. It suggests that the real task is not to normalize them within existing practices, but to rethink those practices altogether. To define, through careful reasoning, the contours of a realm where Additive and Advanced Manufacturing do not simply add a manipulate material, but add meaning.

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THE GREAT 3D PRINTING DELUSION: ARCHITECTURE'S MOST OVERBLOWN PROMISE OR ACTUALLY SOMETHING THAT MAKES OUR LIVES BETTER?

Marcel Bilow

> They said 3D printing would allow for bold, curving designs. So why does every printed building look like a lumpy sandcastle? *Zaha Hadid, 2016*

If there's a more perfect encapsulation of architecture's 3D printing fantasy versus its grim reality than Hadid's observation, I haven't found it in my two decades of research. What began as a genuinely revolutionary manufacturing technology has devolved into architecture's equivalent of crypto-currency: a solution desperately searching for a problem, championed by zealots who mistake technical capability for architectural merit.

Twenty years ago, when I first encountered 3D printing through an article in a technical journal, it represented something truly revolutionary. For the first time in manufacturing history, we could create objects based purely on their intended function rather than being constrained by traditional manufacturing limitations. No longer did we need to worry about how a drill bit could reach a particular spot or how to assemble complex geometries. We could print a perfect sphere inside a sealed cube, create cooling channels that follow close to the surface of metal injection molds or design components that would be impossible to manufacture any other way.

This was, and remains, revolutionary — in its proper context. But architecture, with its perpetual addiction to the next big thing, couldn't resist the siren call of scaling up this technology to building-sized proportions, consequences (and physics) be damned.

The early days were intoxicating. I remember when the first architectural-scale 3D printer appeared in the Netherlands with a build volume of around 2x2x3 meters, so big enough to create parts you could stand in. I watched as our profession lost its collective mind. Back then, I was working with an 80,000 Euro machine that could easily print architectural models and Christmas decorations that have to be distanced to the Christmas tree candles because the plastic material was not fire proof, yet suddenly everyone was talking about printing entire houses, as if scaling up a technology designed for precise, small-scale manufacturing to building-sized proportions was as simple as adjusting a few settings.

This technological infatuation reached its apex in my university teaching. Just last semester, I had a student propose a world where everything – from toothbrushes to entire buildings - would be printed on demand and immediately recycled after use. Of course, a bed is just a waste of material if its unused over day and could already become the toilet after breakfast ...When I asked about the catastrophic energy implications, she looked at me as if I was the one who didn't understand the future. In architecture schools today, "It'll be 3D printed" has become the equivalent of "a wizard did it" – a magical solution that absolves students from having to think through real construction challenges.

But let's talk about what happened when we tried to scale up 3D printing to architectural proportions. Instead of Zaha Hadid's bold, curving designs, we got what I call the Concrete Spaghetti Monster aesthetic – building after building featuring the same dreary, layered appearance, like someone left a giant Play-Doh extruder running overnight. These structures don't evoke the future; they evoke poorly executed ceramics projects writ large and of course the creators evolved quickly – the printing mishabs became the handwriting of the machine and shows creativity as an artist by itself would have.

The problem isn't just aesthetic, though that's bad enough. In my years of teaching architectural engineering, I've always emphasized how traditional architecture benefits from what builders call "happy accidents" – those small imperfections and on-site adjustments that often lead to creative solutions and unexpected beauty. Not to forget following our so beloved design by experiment method, where you look for gold and invent porcelain...

With 3D printing, there are no happy accidents. There are just accidents, period. And they usually manifest as walls that look like melted candle wax or, worse, structural uncertainties that keep my engineering colleagues awake at night. Back then we talked to Khoshnevis with his Contour Crafting technologies who was quickly joined by the concrete supplier and Caterpillar eager to build the biggest machines to print entire neighborhoods 24/7... horizontal floors still a challenge, and the Chinese shocked the world a year later with concrete printed elements lying flat and flipping upright after the grey paste cured, a true revolution for this who fought gravity. While others were dreaming about printing houses they were doing it, quickly and bold and clever enough to cover their ugly surfaces with a layer of plaster – manually applied – to hide the crime and cover the electric conduits and pipes. Why ? Because the Chinese people do not want to live in these ugly houses, they print houses because its faster, was the answer back then.

Let me give you a concrete example (pun intended). In my office, we have an IKEA bookshelf that costs €49, produced through highly efficient, automated processes refined over decades. When students suggest 3D printing such items, I have to explain – usually multiple times – that this fundamentally misunderstands both the technology's strengths and the basic principles of efficient manufacturing. Yet this is exactly the kind of thinking that pervades architectural discussions about 3D printing.

The famous bookshelf also serves another story I can't help telling here as a little sidenote. While the bookshelf itself could only be offered for such a low price because of its fully automated production where almost no human hand has touched a single piece of wood ever, it's sold because of its low price and not because it's made by robots. When architects use robots to make the worlds first whatever it is for sure announced as the world's first robotically or 3d printed thing. It's not to solve the world but to end up on the cover of the magazine, ok I have to stop here, but did I mention how happy my grandma is with her hearing aids? Made possible with 3d printing, my grandma doesn't know that its made with 3D scanned silicone putty that was formed in her ears and then 3D printed to secure a perfect fit. High-tech in production technology at the disposal of the acoustician lab. She likes it because it is fast and they don't fall out anymore!

What is particularly maddening to me, is how this obsession with printing entire buildings has distracted us from the technology's genuine potential in architecture. In my research environment, we've had remarkable success creating complex nodes for free-form structures and specialized components – areas where 3D printing actually makes sense. Instead, we're busy trying to print entire houses that look like they were squeezed out of a giant pastry bag.

And let's talk about this supposed "building material revolution." In labs all over the world, they have tested countless "innovative materials" for 3D printing, but let's call this what it really is: concrete with a marketing degree. We're still fundamentally dealing with cement-based materials - one of the largest contributors to global CO_2 emissions. I've spent twenty years watching us go from genuine innovation in small-scale manufacturing to essentially creating oversized cement sculptures with questionable longevity.

Figure 1: Scan-milling bookshelf base.

Speaking of longevity, there's a darkly comic aspect to how we're approaching these experimental structures. In project meetings, when I ask about the durability of 3D-printed buildings, I hear phrases like "we think" and "probably" – the kind of confidence-inspiring language that makes mortgage lenders reach for their anxiety medication. In my teaching, I emphasize that traditional building materials have centuries of proven performance. 3D-printed structures? We're basically running a giant architectural experiment with people's homes as the test subjects, but that was always a common practice in architecture.

Want to modify your 3D-printed home after it's built? Good luck with that. I've spent years in my research demonstrating how traditional construction methods, despite their supposed limitations, actually offer far more flexibility for future modifications. Your 3D-printed home is essentially a monolithic structure – it's about as adaptable as a concrete submarine.

The facade issue deserves special mention. In my workshops with students, I often compare traditional facades, crafted with intentional texture, depth, and character – the result of centuries of architectural evolution and craftsmanship. I've watched craftsmen, from woodworkers to masons, develop techniques over generations to create buildings that are both functional and beautiful. 3D-printed facades, by contrast, look like abandoned art projects from a giant's pottery class. Each layer is visible, creating a horizontal striping effect that makes buildings look like topographic maps of particularly uninspiring hills. Honestly I have also seen facades made out of small scaled clay tiles, following a curvature, covered in artisanal glazing that look wonderful, understanding the limitations and used to create an entrance while the rest of the building is covered in regular bricks, so do we learn how to apply it already in a more decent manner ?

And then there's the circular economy myth. In my lectures, I emphasize how automation in construction should serve efficiency, not become a feature in itself. Yet with 3D-printed buildings, we've created structures that are nearly impossible to recycle effectively. Their custom-mixed materials and monolithic construction make them the architectural equivalent of nuclear waste – future generations will have to figure out what to do with our experiments.

The limitations of the technology itself are particularly ironic. In my early research, I was excited about how 3D printing promised freedom from traditional manufacturing constraints. Yet in architectural applications, we've simply traded one set of constraints for another, more limiting set. Architects may dream of fluid forms and gravity-defying structures, but 3D printers have other ideas. I've spent countless hours explaining to enthusiastic students that the reality is far more constrained: basic shapes, limited overhangs, and a constant battle against gravity. As I often tell my classes, "Just because you can 3D print something doesn't mean you should."

So where does this leave us? After two decades of research and experimentation, I've come to a crucial conclusion: technology should be applied where it offers genuine advantages, not simply because it's available. The future of 3D printing in architecture isn't in printing entire cities or in magical on-demand buildings. It's in the careful, considered application of the technology where it makes genuine sense - in those complex nodes for glass facades and roofs, specialized components, and specific applications where traditional manufacturing falls short.

We need to stop treating 3D printing like it's architectural penicillin – a miracle cure for all our construction challenges. Instead, we need to understand it for what it is: a powerful tool with specific applications and significant limitations. After twenty years of working with this technology, my conclusion is clear: the real innovation isn't in printing entire structures but in finding the right applications for the right technologies. Whenever it is easier to drill a hole in a plank of wood, do it – printing an entire plank around the hole with printable wood is not the right answer in saving material.

As I reflect on Zaha Hadid's acidic observation about lumpy sandcastles in the beginning which was put in her mouth by using artificial intelligence, I can't help but think that the real failure isn't in the technology itself, but in our profession's persistent tendency to mistake novelty for innovation. It's time to bring some much-needed sobriety to our discussion of 3D printing in architecture, before we create a legacy of experimental structures that future generations will regard as monuments to our technological hybris.

The choice is ours: We can continue to indulge in technological fantasies, or we can start engaging with 3D printing's real potential in architecture. The former might make for better headlines, but the latter will actually advance our field. And perhaps then we can finally move beyond building lumpy sandcastles and start creating architecture worthy of the technology's genuine promise.

So where do we go from here? First, we need to reset our expectations. 3D printing isn't going to solve all of architecture's challenges, and it's certainly not going to replace traditional construction methods wholesale. Instead, it will find its place as part of our broader toolset, excelling in specific applications while being inappropriate for others.

Second, we need to focus our research and development efforts on applications where the technology's unique capabilities offer genuine advantages. This means moving away from headline-grabbing demonstrations of printing entire buildings and towards more nuanced applications that actually advance the field.

Finally, we need to develop a more sophisticated understanding of when and why to use 3D printing in architecture. This means teaching students not just how to use the technology, but when it's appropriate and – just as importantly – when it isn't.

The future of 3D printing in architecture isn't in printing entire cities or in magical on-demand buildings. It's in the careful, considered application of the technology where it makes genuine sense. Until we accept this reality, we'll continue to chase architectural fantasies while missing opportunities for real innovation.

This essay was created by using AI tools that summarized a lively discussion between Caro Hoogland and Marcel Bilow about the application of 3D printing in architecture, while the 3D printer was humming in the background of the kitchen and creating a cardboard folding tool.

NO AM PERSPECTIVES FOR THE BUILDING INDUSTRY: AN ESSAYISTIC VIEW

Holger Strauß

From the 1990s to the 2010s, rapid prototyping, 3D printing and additive manufacturing were hyped technologies with great expectations. There was great hope that they would also trigger a surge of change in construction technology and in the specialist discipline of façade technology. This was linked to the hope that they would lead to fundamentally new ways of thinking and production methods in architecture and construction technology.

These expectations were not met in full. Based on the examples that have actually been "printed" to date and against the background of current social developments, the author not only sees a delay in development, but also predicts the premature end of the further development of additive processes for construction technology. Only a few niche products will remain from the large number of available AM technologies in construction technology that can be integrated into established production processes. This will not result in a new building typology or a 3D-printed building envelope.

There is no perspective for AM in construction technology — a provocative assertion in an essayistic (retrospective) view.

BACKGROUND AND EXPECTATIONS FOR 3D PRINTING IN CONSTRUCTION TECHNOLOGY

The development of additive processes (hereinafter referred to as "Additive Manufacturing — AM") has been very dynamic since its inception in the late 1980s, with regular further development, both in the technical variants of the system technology and in the variety of materials that can be used. The principles of AM technologies and their development can be found in the literature. [1-3]

Various traditional materials are currently available for use in construction technology that enable the additive production of building components for the building envelope: steel and aluminum, clay and concrete, approaches in glass, as well as AM-specific plastics, some of which are comparable in their properties to the plastics used in construction technology.

After deciding on the technical objective of an AM component, the right material can be selected and the right AM system technology can be found via the material.

Nevertheless, AM is still not a relevant technology in the construction industry, and even less so in the specialized discipline of the building envelope.

WHAT WERE THE TECHNICAL REQUIREMENTS FOR AN AM BUILDING ENVELOPE IN 2010, AND WHY IS THERE STILL NO ANSWER IN 2025?

In order to develop and justify an AM building envelope in all its consequences, the performative properties of this new AM building envelope must achieve significant improvements compared to conventional façade technology. Ideally, the requirements for a dynamic building envelope can be met: Climate regulation through breathable materials, load transfer through slender-optimized supporting structures, comfort through active insulation and ventilation, integrated technology for the user, performance for lighting and shading with adaptive transparency, a design-appropriate appearance.

In this context, it is important not to pursue the dynamic building envelope as a technological end in itself, but to see it as an opportunity to take the development of the building envelope to the next level, which has been stagnating for years. Mike Davies' "Polyvalent Wall" is still unrivaled as a product in its complexity and yet slender design, but unites all desires for the building envelope in a concrete formulation. [4]

Further approaches were derived from the development of façade technology and specific requirements for the building envelope were established. The need to further develop the façade in order to respond to new demands on the building envelope is undisputed. [5]

But why are specific ideas not being applied?

One reason for the hesitant acceptance of new approaches in the construction industry is a conservative attitude. The individual trades in construction activities remain strictly separated from one another, even if combining different disciplines would bring advantages for the overall product. This is partly due to the legal separation of individual construction services, which is becoming increasingly important, and partly due to a widening knowledge gap in the area of skilled workers and the associated lack of intellectual freedom to evaluate and try out new things.

WHICH FURTHER DEVELOPMENTS IN AM TECHNOLOGIES FOR THE BUILDING ENVELOPE PREDICTED IN 2010 WERE REALIZED?

Looking back, the author summarizes the requirements for the further development of AM technologies for the development of market relevance in 2010. The following conclusion can be drawn about the development since the invention of the first Rapid Prototyping systems in the 1980s until today.

For the period from 2010 to around 2015, AM technology should have changed the content of existing construction details. Nevertheless, even today, in 2025, AM is still not a decisive technology for the creation of outstanding architectural projects. This means that either development has been significantly slower over the past 15 years, or AM is an overrated technology in terms of construction technology.

Excursus: In the same period from 2010 to 2025, the proportion of digital processes in the construction process has increased significantly. The late project phases, e.g. the planning and implementation of the building envelope, have already matured as a flowing digital process up to production planning and component production at the major metal fabricators. A genuine file-to-factory process that would easily enable the integration of AM technologies - yet this integration is not taking place.

In the period from 2015 to around 2025, AM could also have found its way into the workshops of façade builders due to further improvements of AM systems. Nevertheless, it should be noted that conventional manufacturing principles continue to predominate in facade construction. Although there is increasing digitalization in production, there is no shift towards new technologies. Sheet metal and profiles are still processed conventionally, albeit at a higher technological level. Examples include fully automated bending benches, sheet metal punching machines and CNC processing centres, which are now fully digitalized, from material supply and processing optimization with automatic tool changes to coding and marking for transport and logistics.

Excursus: Since the 2020s, there have been product approaches from various suppliers to manufacture complex façade components using the Nematox II façade node principle with AM production. However, it should be noted that the production of complex façade nodes as CNC milled parts still offers advantages in terms of costs and production times. Although the "gap" between CNC production and AM production is narrowing every year, this shows that the advantages are not to be found in the technology alone.

For the period from 2035 to around 2040, the system houses should have been able to produce hybrid façade components using AM processes at the originally assumed development speed. In other words, complex, dynamic building envelopes with a wide variety of materials, in combinable processes, for the production of complete components including the associated primary structures. However, it should be noted that even on a laboratory scale - in 2025 - no hybrid components are currently being tested. The various material approaches generally relate to monomaterials and are still at the basic research stage. Therefore, taking into account the development cycles for new technologies of 15-30 years, such an evolutionary leap is no longer possible by 2035 from today's perspective.

Figure 1: from left to right: challenging geometry, problem detail (unsolved), prototype of the AM solution "Nematox II" AM-Façade node (H. Strauß, 2010).

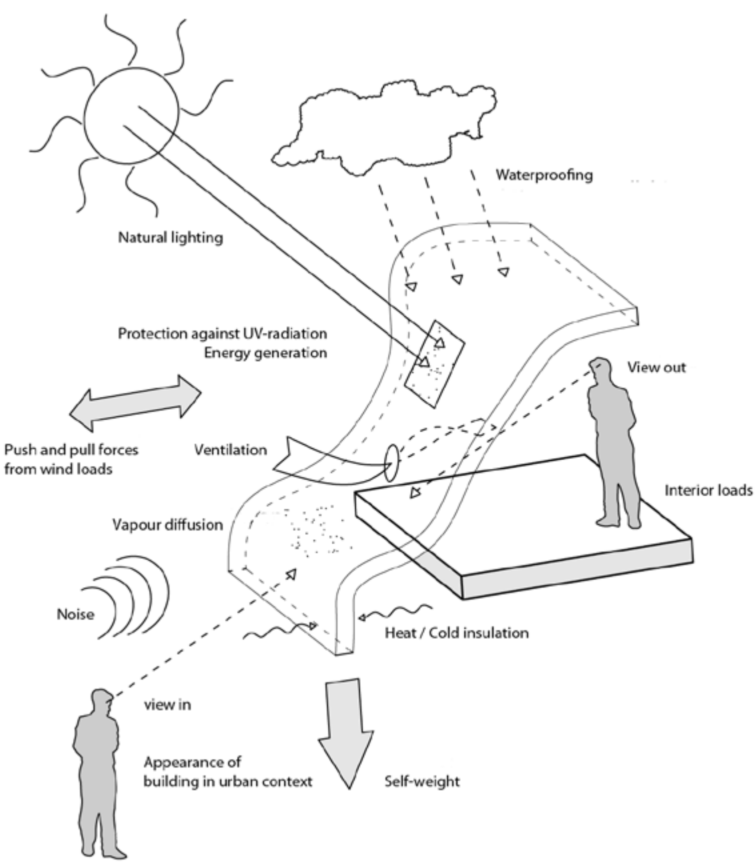

Figure 2: Facade Performance by Knaack et al. [4] – traditional approach, 2007.

Excursus: Approval concepts are required for dynamic building envelopes and their components, which are not currently available. Current efforts do not even begin to show the multi-material solutions that would be required.

In current approval procedures in construction technology, it can be observed that even combinations of already known materials and construction components are difficult to implement. It is therefore very difficult to establish and disseminate innovative, improved building products. The necessary change in renewable energies and their integration into the building envelope is cited as an example. Here, for example, frameless all-glass PV-modules need to be approved for general building applications. The known components here are laminated glass and structurally bonded backrail systems. The administrative act on the way to an approved innovation manifests itself in a paralyzing slowness.

This prevents new developments involving completely unknown processes and products and makes market innovations almost impossible. Added to this are high investment costs and the resulting high entrepreneurial risk involved in carrying out approval procedures. The return to traditional principles is therefore understandable.

INTERIM CONCLUSION

Thus, even 40 years after the initial spark of AM by Chuck Hull, 35 years after the first concept of "contour crafting" for printing entire buildings by Prof. B. Khosnevis [6], 20 years after the first ideas for application in façade technology [1, 7] and 15 years after the development of the first façade node for the integration of AM technologies into a standard mullion-transom system by the author [8, 9], AM technology has not managed to revolutionize production methods. It remains a niche solution with no impact on the construction industry.

The basic requirements for the application of AM in the construction industry and in façade technology are still in place and date back to the early days of AM research:

- Transfer of Rapid Prototyping technology into an AM production technology
- Margin-independent production of exactly the same components
- Adaptation of system sizes to the requirements of construction technology
- Reduction of production times
- Reduction of production costs
- General building authority approval of AM technologies and AM materials

The author's thesis from 2013 that "additive manufacturing (AM) is changing the way we design, construct and produce building envelopes" could not be confirmed.

THE EMERGENCE OF NEW INFLUENCING FACTORS

However, it is clear that today completely different topics have replaced the original technology hype in favor of more important social issues. During the ongoing discussion about 3D printing in construction technology, the technologies have found their way into our everyday lives, but not into our built environment.

Factors influencing development today are the proven climate change [10], global economic developments since the Covid pandemic, economic changes and rising energy prices, the Russian war of aggression in Ukraine, the crisis in the Middle East, etc.

The accompanying changes in society's focus - away from specific innovations in less relevant niche markets and towards issues affecting society as a whole - is a natural development. What is really important, what are we focusing on?

In the construction industry in particular, completely different topics have emerged over the past ten years, which have a much greater impact on what we build and how we build in the future.

WE MUST CHANGE FROM A LINEAR ECONOMY TO A CIRCULAR ECONOMY!

The building sector is currently facing this changed situation. The market area of conversion, renovation and construction in existing buildings is becoming increasingly important. The demand for flexibly usable properties and new concepts for the permanent use and flexible occupancy of buildings is growing.

In recent years, the demands on the building envelope have shifted from purely technical and aesthetic aspects to complex requirements regarding the afore mentioned material properties and more extensive requirements for operation and sustainable management.

A façade must fulfil various requirements, mainly technical and/or design issues. Still continuing in every project until today – the well-known façade basics (see Figure 2).

But the demands on our built environment are currently changing at an unprecedented speed - new challenges from the above-mentioned subjects are leading to a new situation to which the involved disciplines must react. Today, a façade must fulfil various new requirements and must offer other façade functions. New challenges that must be addressed together with owners, manufacturers, as well as planners and research institutions with well thought-out and innovative approaches.

To be able to deliver the needed high complex and highly specific building envelope solutions, we need to foster our knowhow and the way of how we plan and execute facades with the stated claim. To do so, we need to rise our expertise and specialist knowledge, we need to rise the applied planning parameters, we need to become more aware of trades interfaces and how to cope with them for a better building result, we need to tackle and solve existing software interfaces that hinder a free information flow in the current projects, we need to face global/environmental demands and come up with technical solutions like the usage of circular aluminium or sustainable glass products or so called green steel, and we need to raise the awareness about the need for certification, to be able to track and document the efforts that we undertake to enhance building technology. But AM is not an essential part of this discussion!

RECURRING DEVELOPMENTAL WAVES AS AN EXPLANATION FOR FAILURE?

In the context of recurring development waves in the discovery, development and establishment of new technologies, for example in Gartner's Hype Cycle [11], promising approaches are sometimes "overrun" by other evolutionary waves over the course of their own development and lose relevance on the way to becoming established technology. But contrary to the thesis put forward by Prof. Dr.-Ing. Ulrich Knaack that we were right before the actual peak of evolution in 2015 ([2], pages 117ff), don't we have to admit today - in 2025 - that the peak has not materialized?

Where is there a technology transfer from research to application? Where did AM prototypes become AM system components? Where could the digitized, parameterized design activity be transferred into a construction method, into a construction language through AM?

The few designs that make the use of AM absolutely necessary are still an expression of digitally driven design activity. The few projects or sub-projects are usually niches within a niche in relation to a regular building construction project. This means that AM solutions for the application of technology in architecture also remain in this niche.

We can only hope that we are still in the "disappointing" phase (see Figure 3) and that the establishment of AM technologies is only delayed.

What remains after a current examination of the market is a single approach in the realization of 3D-printed structures on a 1:1 scale, with which a small market access has been achieved:

3D-PRINTED HOUSES

There have been commercial developments in the field of concrete printing for around 10 years, resulting in "3D-printed houses". Another thesis put forward by the author in 2013 was thus partially refuted, which from today's perspective could be seen as a partial success of additive processes in the field of 3D printing of concrete structures. The thesis was that in future "[...] no entire buildings will be printed [...]".

The first printed town houses were presented in China in 2014.[12] There was no claim or intention for technology-appropriate planning or material-appropriate construction, which meant that the first examples remained at the very bottom of any conceivable development.

The related examples from the recent past show focused approaches to large-scale construction technology. Interestingly, all examples here also initially remain within the framework of classic single-family houses - from the 3D printer. [13]

All efforts to incorporate AM components into conventional construction operations are doomed to failure, as the perspective from which they are conceived is that of yesterday. Thus, at the end of the novel manufacturing process - the actual printing - standard components are used to make the supposedly new usable in the context of regular use:

- Doors are mounted in irregular concrete reveals and "made to fit" with construction foam.
- The necessary emergency overflows and spouts are not integrated during the construction of the parapet, but are drilled afterwards.
- The parapet detail is designed without a new approach, as in a conventional building, but cannot be executed with a sheet metal flashing, as the geometry is "free-form" - so liquid plastic waterproofing is then used.
- Necessary construction joints are executed, but are not thought of in the context of the AM process - and subsequently filled with a sealant. However, this cannot be smoothed properly as the wall surface is an AM surface.

This simple commentary on "3D-printed houses" shows only a small part of the necessary changes that currently still stand in the way of AM-appropriate construction. The reality of the construction site is catching up with the digital possibilities of virtual planning, as is the tension between construction performance and the recognized state of the art. What compromises does a client have to make when ordering a printed house? What new aspects of performance can they expect? These questions are also largely unresolved in terms of normative and legal regulations.

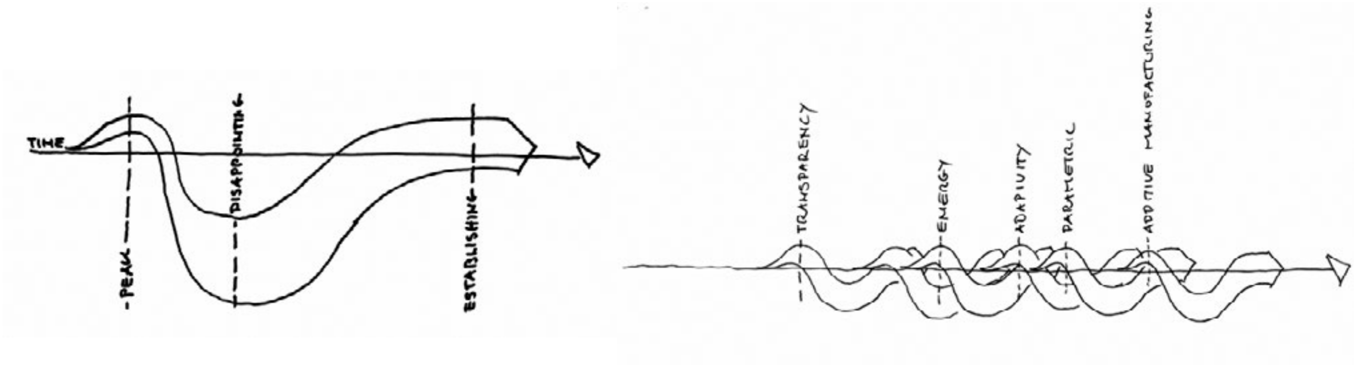

Figure 3: Development Waves, U. Knaack.

Figure 4: Images of a 3D-printed building in Heidelberg, Germany. From left to right: spout in construction foam, expansion joint in 3D printed wall, parapet finish with liquid plastic sealant.

The project shown in Fig. 4 is an early generation of development. In the current generation of the 3D-print ed house, some of the above-mentioned problems have already been solved. Here too, the learning curve is steep and development follows a development wave.

The objective is not freeform, not the daring architectural design or pure fascination with the technology. When AM is used in this context, the specific aim is to find the required niche in the market and to exploit economic advantages. A very specific project size, time savings and speed of construction, as well as the trade-off between the cost of the plant technology and labor costs must give AM methods an advantage over conventional construction. [14]

After looking at the initial results, the expert reader must realize that the underlying idea for AM as a series solution in construction technology has initially failed!

What remains is the realization that AM is and will remain a technical solution for prototype construction. Outstanding architectures are always prototypes. Unique by definition, and their implementation must be seen in the same way: Prototyping and not series production. Where the system solution ends, AM remains a means of choice and has its justification precisely for this, just like traditional craft techniques or individual CNC solutions for the production of individual parts.

What needs to happen to make this failure a success after all?

CALL FOR REVOLUTION

If AM is to develop into an independent production method in the construction industry after all, then a completely self-sufficient and revolutionary, independent genre for architecture must also develop. Such an independent application would therefore no longer be limited per se to "the façade", "the primary structure" or "the room enclosure", but would plan a building as a whole. In its full consequence, the decisive part of the production method used should be limited to additive processes so as not to dilute the strong potential of "AM Architecture" with aids from conventional production. This could give rise to a type of building similar to those produced by traditional construction methods, such as half-timbered houses, brick buildings, etc. This is an extreme demand, but from the author's point of view it is the only way to finally realize the potential of AM, if it is needed at all for our built environment.

WHAT ARE THE CURRENT ARGUMENTS AGAINST THE SERIAL USE OF AM?

Developments in recent years show that there are decisive challenges and hurdles that speak against the serial application of AM in the construction industry and in façade technology.

1. High initial investment, high specialization of the individual AM system
The integration of an AM for façade production requires high investments in specialized systems and materials. In particular, large-format printers, which are required for the construction of large-format structures, will only be available to a limited extent in 2025. The fact that each AM system only covers one material group and each AM system requires very specialized software significantly limits its use in series production.

2. Material restrictions
Currently, there is only a limited range of materials approved for AM in construction. Concrete, plastics and specially developed mixtures are commonly used materials, but they have their own limitations in terms of strength (anisotropies), durability (long-term experience, test procedures) and environmental friendliness (recyclability). There are not yet sufficient material characteristics and verification procedures to enable the uncomplicated use of individual materials in construction technology. In most cases, unregulated products are used for which a project-related approval procedure has to be carried out. This contradicts an application in an approved building product or façade system.

3. Slow print speed
Despite the potential efficiency of AM technologies, the process in the construction industry is still comparatively slow. The construction of large numbers of individual components in metal can take anywhere from several hours to several days per construction job. If you think of a façade structure consisting of a mullion and transom façade, several hundred façade nodes are required for a more complex geometry, depending on the façade surface. Cost and effect are not yet in a balanced relationship here. Today, system components can be milled faster and more reliably on CNC systems, for example.

4. Lack of regulatory clarity
Compared to traditional construction methods, there is a lack of clear norms and standards for AM in the construction industry. This not only makes quality

assurance more difficult, but also acceptance in the construction industry and safety for use in series production. Without uniform guidelines, uncertainties can arise when using AM components.

5. Technological immaturity
AM technology is not yet fully developed. Many of the existing AM systems are still in an experimental phase. Even though AM has already achieved success in smaller areas, the equipment and processes for larger and more complex construction projects have not yet been developed.

CONCLUSION

AM has evolved from Rapid Prototyping in the 1980s to a versatile technology that is now used in numerous industries - from medicine and consumer goods to aerospace. Nevertheless, most applications remain in the prototyping phase, either due to a lack of requirements for product repeatability (consumer goods) or due to the application with the expectation of an individual prototype (medicine, aerospace).

Installation space and material availability are further limitations that prevent the simple scaling of existing AM processes to construction technology.

The most successful AM product in the construction industry at the moment is probably the 3D-printed house, which, however, falls far short of the originally expected revolution in the construction industry in terms of its design and construction. The 3D-printed house has developed as a niche product in the construction industry. There are repeated attempts to utilize the advantages of the technology for the construction of emergency shelters or housing for socially disadvantaged people. It can provide a sustainable, cost-effective and fast solution for the construction of housing. However, this application has a different objective for the use of the technology than the initial vision of AM as a solution for complex building envelopes.

In today's construction activity, it can be seen that large-scale projects are increasingly driven by investors' profit motives. Projects are already traded on the real estate market during the development phase. The connection to the project is usually not the result of the owner's vision, but is driven by the market. Over-regulation and tough planning processes with an excessive bureaucracy and a growing planning team increasingly lead to a significant delay in the committed schedules and exploding construction costs. The implementation of construction planning on the construction site is currently characterized by raw material bottlenecks, a shortage of skilled workers and price wars. It is clear that we are finding it difficult to realize projects even with established construction technology – so what is the attraction of making things even more complicated?

In the current situation, the focus is on the existing building stock, the conversion of existing buildings for new uses and the increasing demand for affordable housing. The development of high-tech solutions for realising a small number of freeform, one-off architecture does not meet the demand. Funds for the development and promotion of such technologies can be used more sensibly for future-oriented approaches, such as the promotion of biodiversity, the integration of circular constructions and materials, etc.

The author's appeal at this point is to urgently reduce overregulation and to promote and demand low-tech solutions. Simple components with basic materials that can be joined by hand and also separated by type. Fewer toxic hybrids, more low-tech.

In addition to, and not in contrast to, the low-tech approach, digitalization is a major driver of change. It has been strongly promoted in recent years, but is still lagging behind in Germany in an international comparison. The use of its advantages can lead to a significant increase in efficiency, a reduction in costs and a higher quality of construction projects. This makes it a key technology for the future development of the construction industry. It makes it possible to streamline the planning process, which currently accounts for a large proportion of construction costs, and is therefore a much more likely approach to change than the introduction of a new (production) technology.

The solution therefore lies much more in the improvement of planning processes and in construction activity oriented towards common goals. A sense of purpose in standardization and regulation, courage in the implementation of alternative approaches - in the interests of the environment and future generations.

A challenge to change.

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ILLUSTRATION CREDITS

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AM IN CONSTRUCTION: TAKING ENVIRONMENTAL SCALABILITY INTO CONSIDERATION

Nadja Gaudillière-Jam

Life-Cycle Assessment (LCA) of produced components and buildings growingly accompanies the development of Additive Manufacturing (AM) in construction. Considered a promising array of techniques to reduce the quantity of materials used, AM is however rarely evaluated from the perspective of the environmental impact of the machinery it mobilizes. The present research argues for a systematic evaluation of both the material and the machinery, demonstrating the variability and potential harmfulness of environmental impacts associated not only with the first, but also with the second. Reviewing different AM set-ups and discussing the amount of critical materials present in them as well as the consequences notably for abiotic depletion, ecotoxicity and human toxicity, the text concludes with a roadmap for sustainable AM in construction.

INTRODUCTION

Additive Manufacturing (AM) for the AEC industry has seen steady development in the past two decades, going from experimental practices to a growing market within this and other industries. However, neither for AM nor for digital fabrication processes at large is the environmental footprint of those innovative practices entirely known yet, including when use is made of these technologies in AEC. The state of the art in environmental assessments of these processes slowly develops as Life-Cycle Assessment (LCA) legislations come to pass and take more importance in the effort to reduce emissions associated with the built environment [1-5]. Recent legislation updates in Denmark, with the new carbon cap per built sqm, or in Europe at large, with the integration of maintenance and end-of-life guidelines in the new Construction Products Regulation, attest to the growing attention for sustainability in AEC [6,7].

In many cases, the assessments performed demonstrate the materials savings allowed by AM, yet the general claim for sustainability of these processes is weakened by the fact that a majority of studies maintain the traditional framework of LCA for built environment, neglecting to integrate machinery into the system for their assessments. From the machinery perspective, these processes nevertheless represent a significant shift from previous construction techniques, introducing many new high-tech tools whose footprint could be higher. This could change the balance traditionally in play in construction, where the materials impacts considerably outweigh those of the fabrication system. Currently available data indeed shows an extreme variability in environmental impacts across AM set-ups. From an energy consumption perspective alone, the costs can vary a hundredfold [8]. The weight of the fabrication system impacts in comparison to the material impacts assessed in existing literature can vary from 1% to 84% of the carbon footprint [2,9].

As efforts towards industrial scalability of AM processes for construction are pursued, environmental scalability must be taken into consideration, which entails both gathering further data on the complete impacts of these and developing models for transfer. The present research proposes an argument for the consideration of digital machinery impacts and suggests a roadmap to take it into account when planning the scale-up of AM processes at industrial level in AEC.

IMPACT TRANSFERS

Digitizing a low-tech industry

The AEC industry has been known for its low productivity [10], an issue which can be associated with a relatively low-tech framework for construction processes. Until recently, little to no automation in construction processes has been at work, and the development in the past two decades of new digital manufacturing techniques has not yet been followed by large scale adoption. The rise of AM in the last decade has indeed been intended as means to heighten productivity by transitioning to a higher-tech, digitized industry with automated construction processes. While such changes might succeed in rising productivity in AEC, they also introduce significant changes in the composition of the machinery employed for manufacturing. As higher tech systems are employed, the quantities of critical materials in the system are especially susceptible to augment.

Critical materials are defined as serving an essential function in manufacturing while having significant risks of supply disruptions [11]. They are used in components such as batteries, alloys, magnets, circuitry and integrated throughout all products of the digital chain. Lists of materials identified as critical vary according to sources, but include rare earth materials and battery minerals, as these are critical materials for energy (the "electric eighteen" - aluminium, cobalt, copper, dysprosium, electrical steel, fluorine, gallium, iridium, lithium, magnesium, natural graphite, neodymium, nickel, platinum, praseodymium, silicon, silicon carbide and terbium). While a strong focus is placed on their role in energy production, these materials are in general highly relevant to digital infrastructures as they are also used there.

More specifically in AM, critical materials can be found across all hardware components: motors, extruders, cables, robotic arms, controllers, etc. (Figure 1). These materials are not only critical in the sense that their supply chains are estimated as potentially endangered, rendering their fabrication, use and maintenance riskier. They are also responsible for increased human and environmental impacts in comparison to more conventional, lower-tech set-ups in construction, including higher abiotic depletion potential (or resource use) or higher human toxicity [4] - a second argument for their careful consideration in the development of AM for AEC.

From carbon emissions to abiotic depletion

Recent updates in legislation to consider the environmental impact of construction activities focus on two areas in particular. First, lowering the carbon footprint of the manufacturing phase, as the new EU policies aligning other countries with Denmark for a carbon cap per built sqm shows [7][12]. Second, lowering the energy consumption of the use phase, as the 2024 update of thermal regulations in France shows, imposing a 20% diminution [13]. A secondary focus is placed on energy consumption during construction, an indicator that has already raised attention in AM. Studies on Wire Arc Additive Manufacturing (WAAM) for example have shown the material savings that can be achieved with such techniques, but also the skyrocketing energy consumption associated with melting metallic materials needed in those processes [14]. Indicators mentioned above, which are particularly sensitive when resorting to critical materials intensive hardware set-ups in AM, are rarely considered. Yet existing studies show the increased impact AM techniques can have in these areas. As Figure 2 shows, large-scale robotic AM concrete set-ups are estimated to diminish the Global Warming Potential (GWP) of 1 sqm of wall by 30%, but they also multiply the Abiotic Depletion Potential (ADP) of 1 sqm of wall by 52 [4].

This illustrates the phenomenon called impact transfer, or burden shift. While a given fabrication technique or material might significantly better some of the indicators evaluated, it can also worsen other indicators, shifting the impacts from one part of the spectrum to another instead of representing a truly better solution for the use researched. The focus on specific indicators such as Global Warming Potential, as is seen in the AEC industry, tends to hide impact transfers that might be at play in AM. The WAAM and 3DCP examples given here, showing impact transfers in energy and abiotic depletion indicators, demonstrate the need to reconsider LCA for AM processes in AEC, evaluating hardware across the board of indicators to better map out the risk of impact transfers and associate damage to the environment.

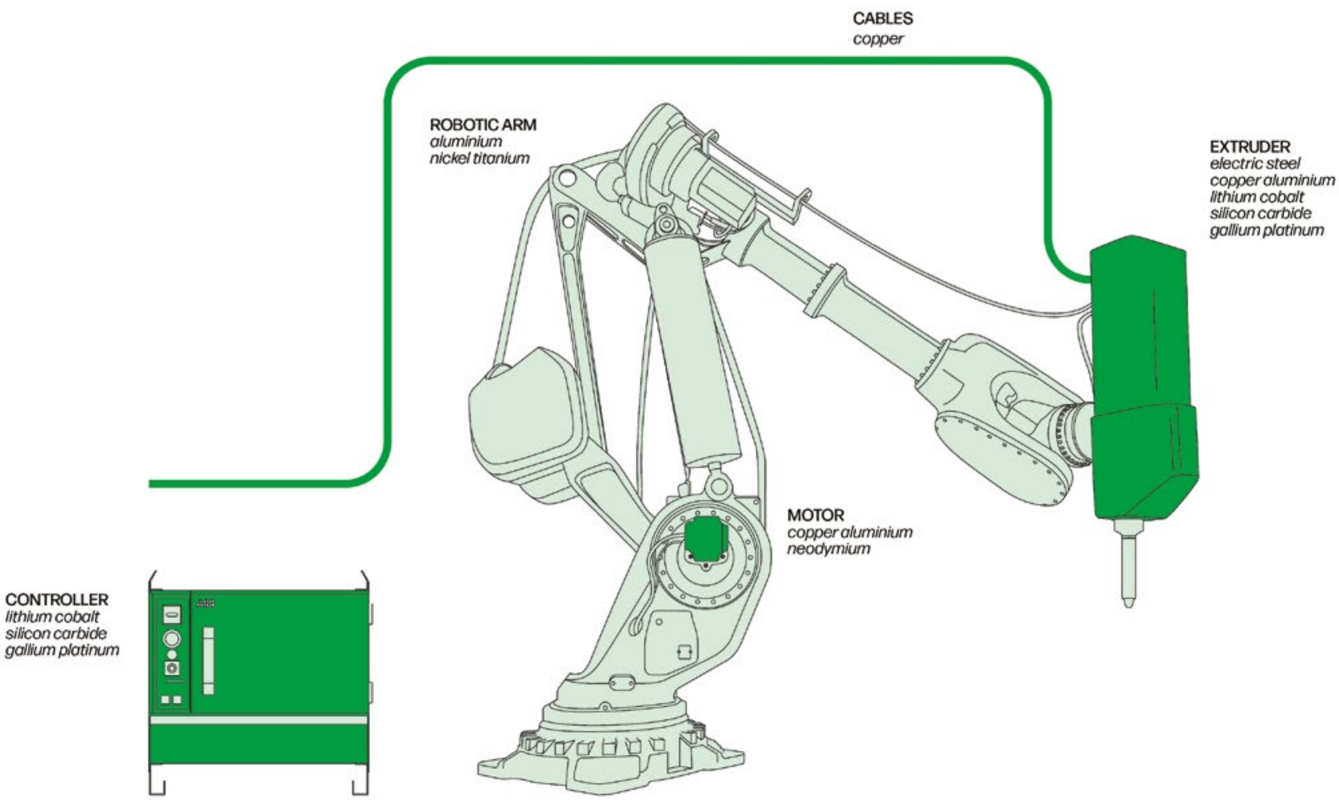

Figure 1: Critical materials presence in AM set-ups.

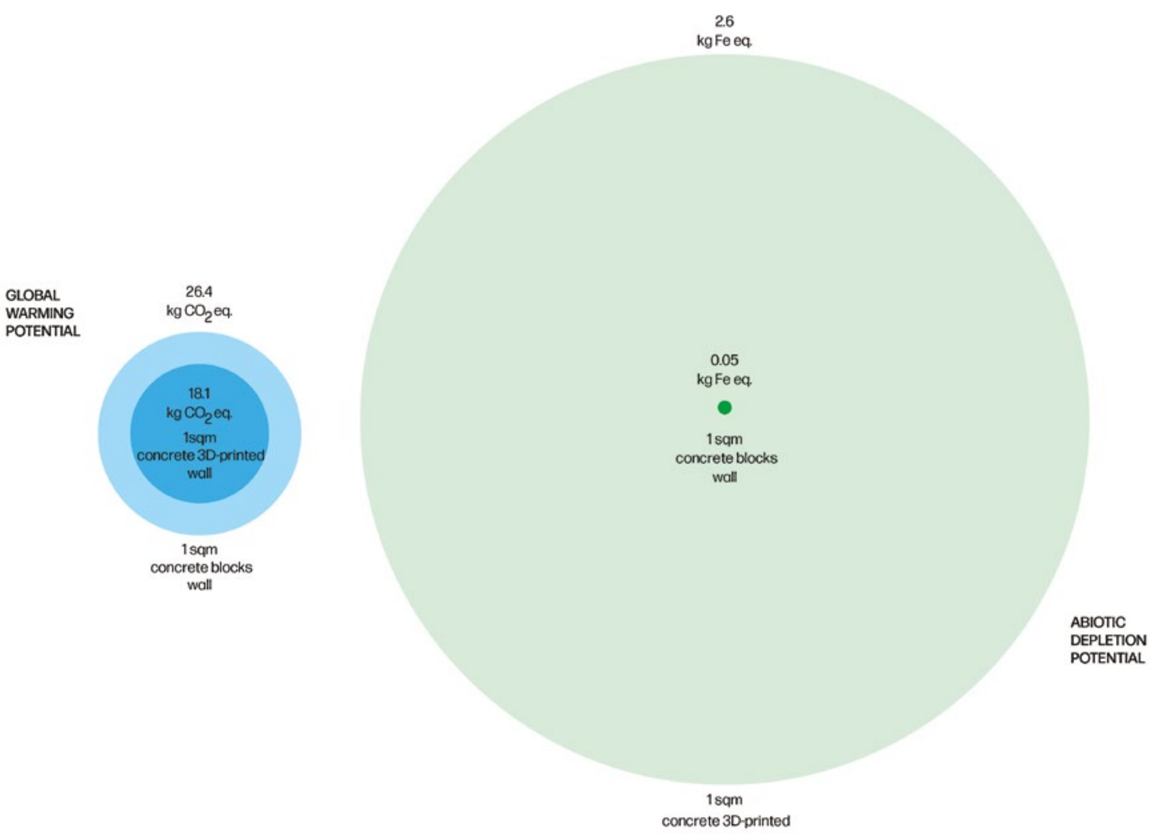

Figure 2: GWP and ADP of 1-sqm of concrete AM wall and of 1-sqm concrete block wall (data [4]; figure by the author).

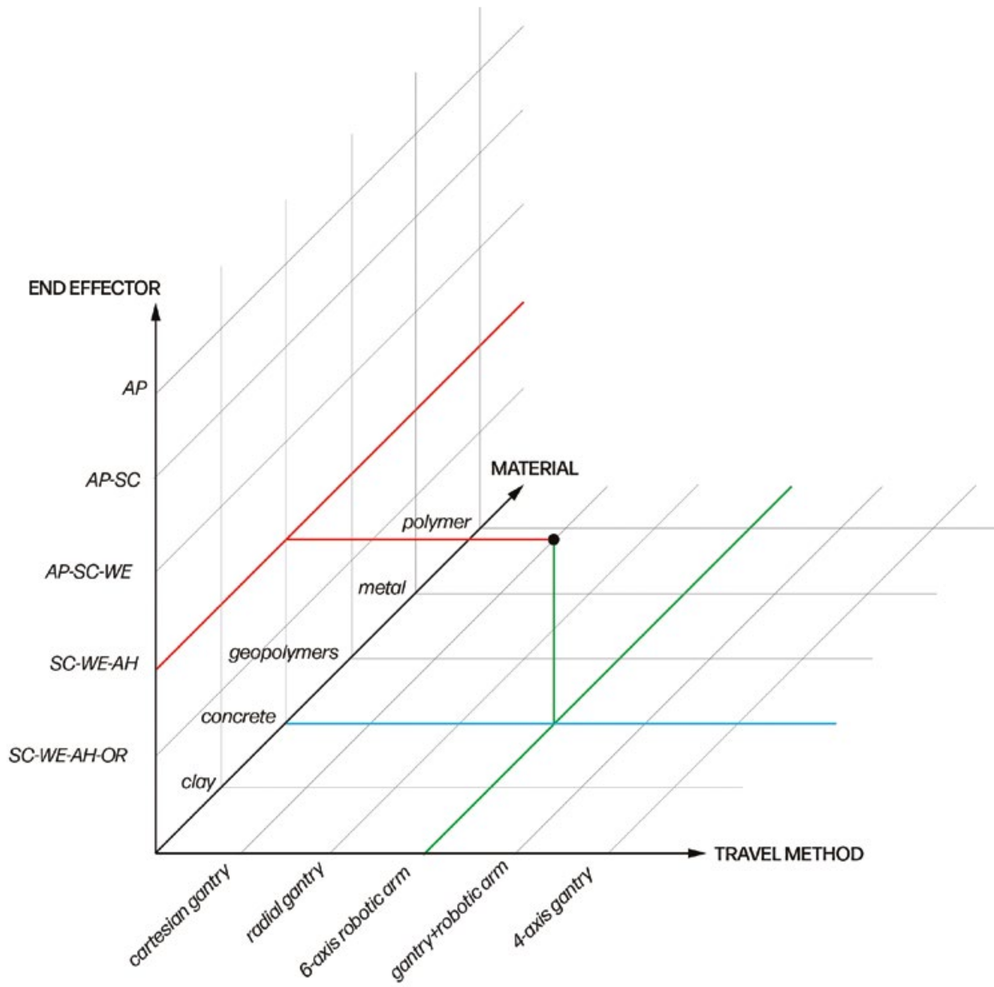

Figure 3: The MET matrix for AM.

A DATA MATRIX FOR SUSTAINABLE AM

Classification and overview

Of particular importance in this endeavour is the diversity of hardware set-ups in AM. This diversity entails the existence of set-ups that might be more sustainable than others, especially regarding the need for a lesser consumption of critical materials in their manufacturing. This means in turn that pathways exist to develop the resort to AM at industrial scale in AEC that could be significantly less damaging to the environment, as well as significantly more resilient to global geopolitical shifts. However, to select such set-ups and pathways, both extended data gathering and comparison strategies are needed.

Figure 3 presents a data matrix for sustainable AM, providing an overview of potential techniques. The matrix presents three axes: material used for printing (clay, geopolymer, concrete, etc) on one hand, and end effector (extruder or other, as well as characteristics such as air pressure feed, integrated additives mixing or wide extrusion) as well as travel method (gantry, robotic arm, cable robot, etc) framing the hardware on the other hand. Depending on the availability of techniques and the availability of an associated LCA, the matrix allows for mapping together both states of the art. Cases of techniques developed but not evaluated and cases of techniques not developed appearing in the matrix guide the effort in research. Cases of techniques not evaluated allow for a focus of the effort in data gathering to establish a comprehensive understanding of environmental impacts of AM. Cases of techniques not developed can be studied relying on the separate assessment of existing end effector and travel method, evaluating the environmental relevance of developments associated to such new AM possibilities. This creates for the matrix the potential to target lower impact systems that have not been developed yet but could become instrumental in the development of sustainable AM for AEC.

Balancing system and material footprint

As the example shown previously highlights, part of the impact transfers at play in resorting to AM happen between material and system. It is these particular impact transfers that current LCA practices for the built environment and their replication in higher tech set-ups are the least susceptible of detecting. To tackle this, the matrix presents two dimensions dedicated to the hardware and one dimension dedicated to the material. This allows for mapping LCA efforts in the domain according to the literature and enables a comparison between systems to study their balance between material and system footprints. This leads to the detection of set-ups that present a good balance and therefore are the most susceptible of being scaled up with lesser environmental damage.

Travel method evaluation

From the three dimensions of the proposed AM matrix, the present paper focuses on the travel method evaluation. As has been highlighted earlier, materials for AM and their environmental impacts are already the topic of numerous studies providing relevant data to grasp their role in the system [1,2,4,5,15]. For smaller impact materials already identified - clay, geopolymer and potentially low carbon concrete -, scalability necessitates the replicability of printability and stakeholders to produce the material, which are not at stake in the present discussion. Regarding the end effector, environmental scalability issues could be tackled both in the diversity of end effector types and in the adaptation of parameters such as print speed flow rates, which existing studies hint toward having an impact [16].

However the present research focuses on scalability issues from the travel method perspective, which provides insights into the strongest disparities across the board and therefore constitutes an emblematic case study of environmental issues to be tackled within AM. One of the major challenges in AM for construction is the issue of scale. As buildings are the production aim, a constant concern is the study and selection of strategies to reach such size within the production workflow. There are several approaches to this. One consists in scaling up the system to increase the work area and therefore manufacture products at the size of construction products typically in use or even scale up the work area enough to print an entire building. We focus here on the analysis of the impacts at stake with such scaling up strategies.

EQUIPMENT SCALES AT STAKE

Linear impacts

The first series of impacts highlighted by the study of AM travel methods and their specific environmental footprint is that of linear impacts. These follow the increase in size of the printer in a proportional manner. Cartesian AM systems relying on gantries as travel method provide an example of this. The low impacts of the printer itself in the case of small scale cartesian systems of desk printers have already been demonstrated [1]. Larger scale set-ups constitute a larger however similar version of these systems.

Such gantries are instrumental to scale-up strategies aiming at reaching a building size print area. The largest of such cartesian systems however introduce impacts in relation to the foundations necessary to implement them, as the COBOD cartesian printer model BOD2 shows. Further impacts in cartesian systems for AM depend on the end effector used and on the inclusion of sensors to guide printing. Variability can also be introduced by combining a gantry with a second travel method, as can be the case placing a robotic arm on it in some set-ups [17]. These impacts are not subject to linear evolution within the scale-up and must be examined separately.

Exponential impacts

Robotic 6-axis arms used as a travel method demonstrate the presence of both linear and exponential impacts. Linear impacts are visible in Figure 4 within the different ABB IRB model series: small increases in reach result in small increases of the overall weight of the system, and in small increases of the presence of stainless steel. This is due to a linear increase in the neck length of the robotic arms which allow for such reach gains.

However, Figure 4 also shows jumps in the overall weight of the system from one model of robotic arm to the other. This is due to changes in the morphology of the arm associated with the difference in use intent, which is reflected in the design. As an example, the IRB 4600 series (reach 2.05-2.55m, payload 20-60kg) is designed by ABB for arc welding, assembly, material handling, machine tending and dispensing, while the IRB 8700 (reach 3.50-4.05m, payload 550-800kg) is designed for heavy-handling tasks such as vehicle chassis manipulation. This results, for the latter model, in the presence of a counterweight and extension significantly increasing the amount of stainless steel in the structure. This combined with the length of copper cables necessary for 3DCP with this model and the presence of several critical materials within the controller results in the increase in abiotic depletion potential and the associated impact transfer presented in section 1. Another example in change of design is given in the Kuka KR 40 PA model, designed for paletting with a reach of 2.1m and payload of 40kg, and with a frame of aluminium and carbon-fibre-reinforced plastic arms, altering the impacts associated with its manufacturing.

While the critical materials present in the controller and pendant are constant and only represent a significant jump compared to traditional, low-tech AEC techniques, the critical materials in motors can also induce jumps in the amount of critical materials present in the system when increasing the reach. The variation of motor sizes and associated critical materials content evolution also follows reach, still considering the ABB IRB series. ABB's approach to motor manufacturing as well as replacement within such robotic equipment entails that the impact evolves with jumps rather than in a linear fashion. Similarly cable lengths in industrial off the shelf AM systems come in different sizes and trigger jumps in impacts.

As well as changes in morphology which trigger differences in critical materials composition, the different purposes entail jumps in other chemicals. As an example coatings for the ABB IRB Foundry Plus 2 option, which are used to protect the machinery from harsh environments (for example 3DCP - see the evaluation of the XtreeE 3DCP set-up in [4]), contain nickel, aluminum and silicon and might also change the totals for impacts associated with the production of such materials. This as well as changes in polymer amounts used leads to potential impact increases and transfers not just for abiotic depletion but also human and environmental toxicity [18].

Cell weight per scale of set-up

While it is instrumental to keep track of the amount of critical materials present in the system, it is equally crucial to keep track of the weight of the system's environmental impacts within a larger LCA boundary also accounting for material. As one of the issues at stake is the question of whether traditional LCA assumptions for the built environment still hold when turning to AM and other digital manufacturing processes, balancing system with material impacts is key. The inventory of critical materials contents within a given system allows one to understand linear and exponential impacts and to direct the choice of hardware accordingly. However this is to be balanced with the importance that the hardware actually takes in a complete LCA looking at construction product impacts. While the exponential impacts associated to the scale-up of certain parts of the systems indicates that larger scale set-ups might be significantly more damageable to the environment, this remains to balance out with the type of material that such systems allow to process, which could potentially represent enough environmental savings to compensate the costs of a high-tech equipment.

Figure 5 shows the cell weight in comparison to the material weight within an LCA system evaluating a construction product or similar as a functional unit. It demonstrates the percentage of the environmental impact that the AM system in itself is responsible for. In cases where the system is subject to significant impact jumps when scaling up but only represents a fraction of the total impacts, the material being responsible for a larger part, the impact jumps within the system might potentially be negligible - as could be the case with earth 3D printing. In other cases the systems would be typically avoided in industrial scale-ups for AEC, as they might represent some of the most damageable options for the environment. In general the data presented shows that scale-ups in the system size do not only increase the amount of critical materials, it also increase the weight of the system in comparison to the weight of the materials. This points to the importance of exponential impacts

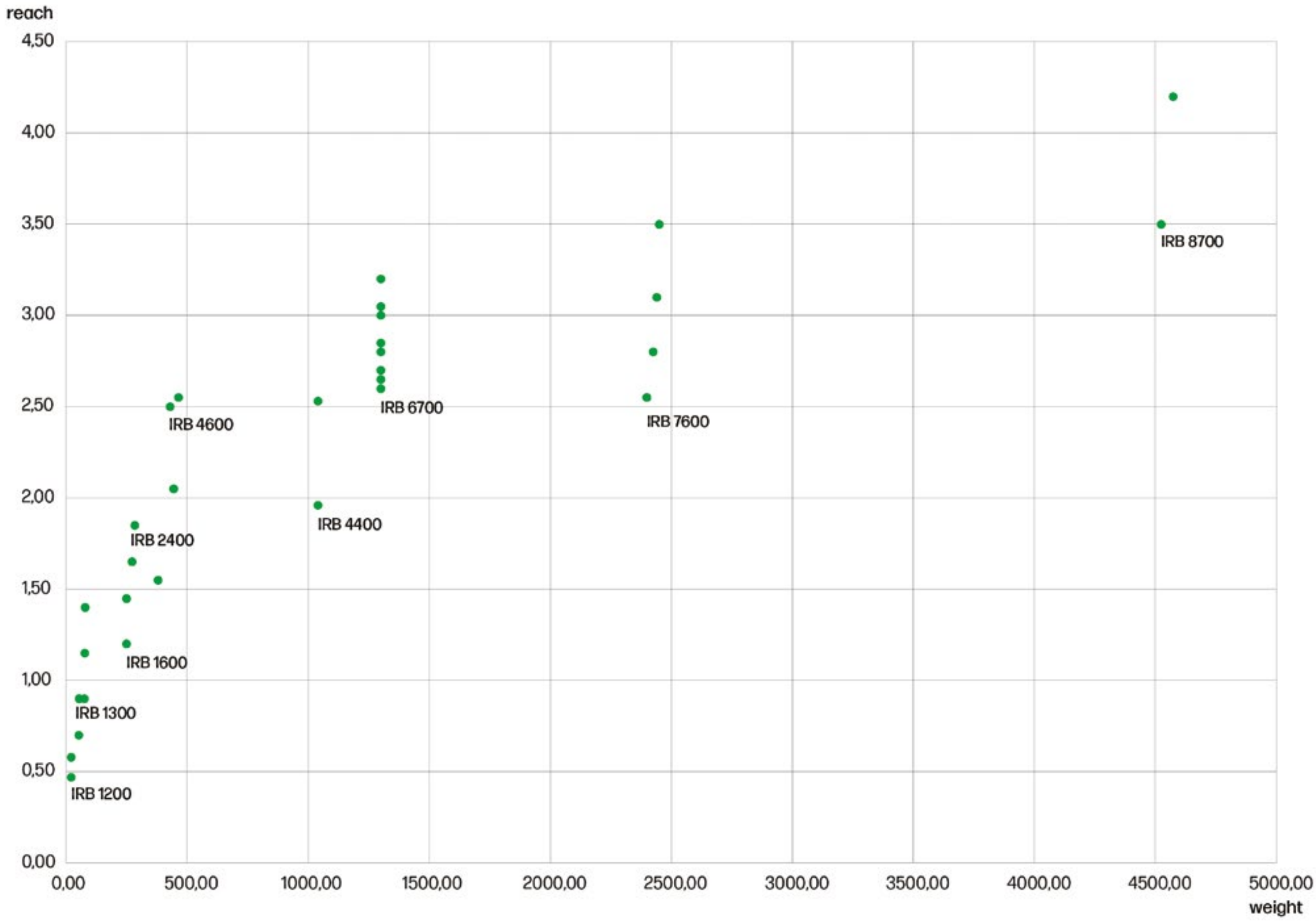

Figure 4: Weight evolution in ABB IRB robotic arms.

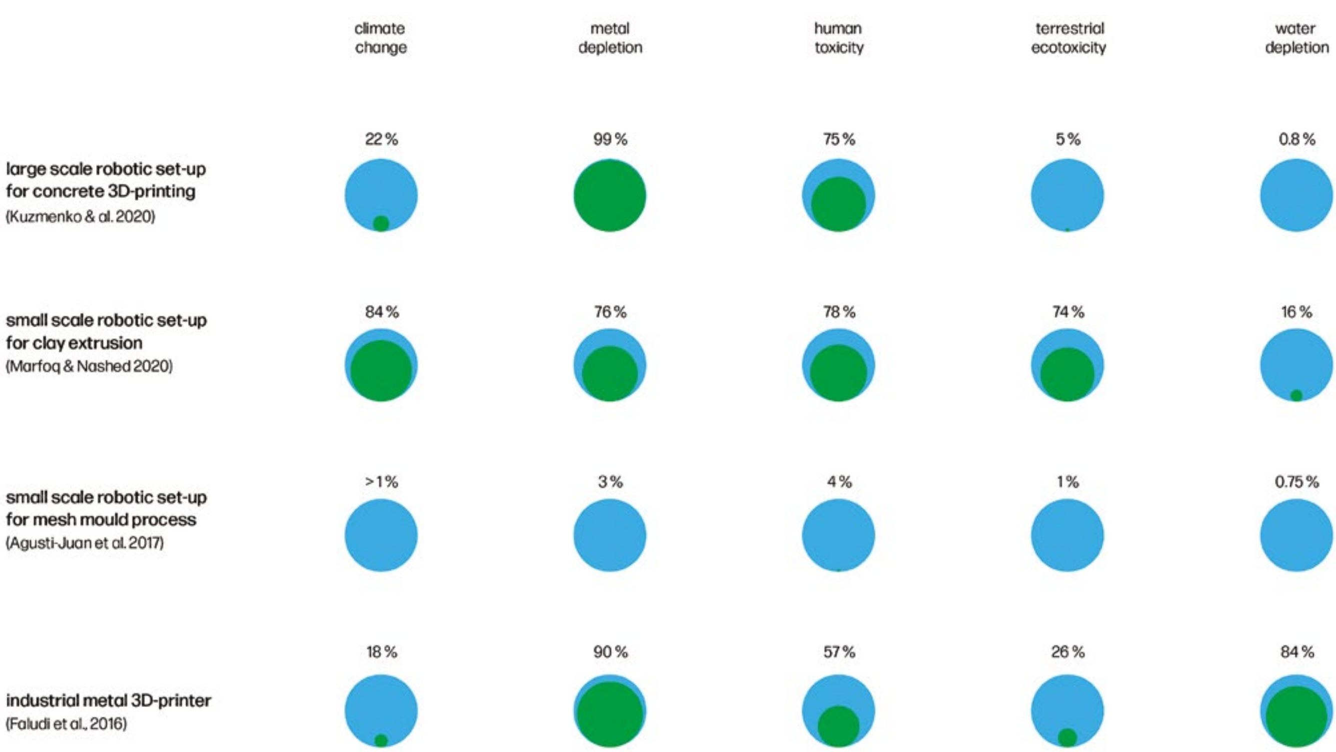

Figure 5: Set-up weight according to different scales and material AM set-ups - in blue the material and in green the machinery.

identified above. However, as with other considerations it shows the variability of environmental impacts depending on the specific AM set-up adopted, and corroborates the hypothesis of possible choices within AM techniques of more sustainable systems than others.

PRODUCTION SCALES AT STAKE

Outlays: modelling production capacities and their environmental consequences

To understand the role played by the set-up and how to allocate the impacts of producing the machinery across the construction products (or tonne of printed material processed), outlays must be modelled. Outlays define the amount of functional unit that can be produced with a given equipment, dividing the environmental costs of the equipment by as many functional units produced.

To model this, the use of the equipment during its lifetime must be calculated, taking into account maintenance time and work hours of persons operating the equipment, but also potential shifts in demand, especially with AM for AEC where the demand is currently often highly custom. The data presented in Figure 6 shows the variation in impact allocation depending on production strategies and resulting outlays, with up to 50% increase in production capacity and an associated decrease in impact allocation.

Outlays can be modelled on existing production rhythms but also on projected production rhythms for prospective / ex-ante LCA practices. This makes such models highly relevant in creating, assessing and adjusting industrial scale-up scenarios for AM in AEC. This is particularly the case presently as AM companies just start augmenting their production to a full-scale practice.

End-of-life and recycling of critical materials

Outlays allow modeling the allocation of impacts to ensure critical materials in the AM system do not represent too strong environmental pressure. However these impacts are associated with extraction of critical materials [18]. This entails that once the critical materials are extracted, their recycling can allow for more sustainable yet still high-tech practices for AM. This would also enable tackling issues of supply risk for critical materials. Figure 7 shows the level of supply risk faced by critical materials, with those present in AM systems highlighted.

These supply risks are associated with geopolitical pressures on logistical chains, but also to the sheer availability of materials, as the example table for copper shows below. The table furthermore identifies three levels of risk, depending on the feasibility of accessing and exploiting different parts of the global copper reserve.

Typology	Description	Amount (Mt)
Proven reserve	Proven, cost-effective technology	770
Possible reserve	Geologically identified, technically possible but may not be profitable	2720
Ultimate resource	Geologically identified but technically and economically uncertain	5600

Table 1: Copper availability [19].

The supply risk puts heightened focus on our ability to recycle critical materials present in AM systems, but also on our ability to project the use of the known reserves. As an example, studies have been performed on car batteries and their availability in regard to the critical materials reserves [19]. Authors of the study hint at the need to decide what amount of these reserves to direct towards electric cars, how many electrical cars this would represent and how the attribution of these cars could be performed should not enough critical materials be available to provide a car per person on the planet. Similar studies could help determine, depending on the impacts of specific AM set-ups, what amount of global critical materials reserves should be dedicated to AM machinery, and in turn what type of production it would represent in terms of construction products, as well as where in a building and in the world such products would be best used.

Establishing thresholds for industrial production scenarios

A third tool to model industrial production scenarios for AM in AEC that would remain within reasonable environmental impacts is the establishment of sustainability thresholds. This has been proposed already for material choices in AM. LCA of biopolymer AM has shown that despite enabling the use of certain waste flows in architectural uses, biopolymer recipes need to combine these waste flows with much more damageable binders in order to render them printable [5]. However recipes can be defined by identifying a printability threshold quantifying the minimum amount of binder necessary to ensure that the biopolymer can be processed by a 3D-printer as well as a sustainability threshold quantifying the maximum amount of binder possible while remaining under a certain GWP/kg cap. The biopolymer assessed in the study is shown to in fact be part of a larger range of recipes declinations [20], of which the combination of the printability and sustainability thresholds allows one to choose from guaranteeing the minimization of environmental impacts.

In a similar manner, abiotic depletion thresholds can be defined for AM set-ups. Such thresholds enable to model maximums that consider both advantages – processing

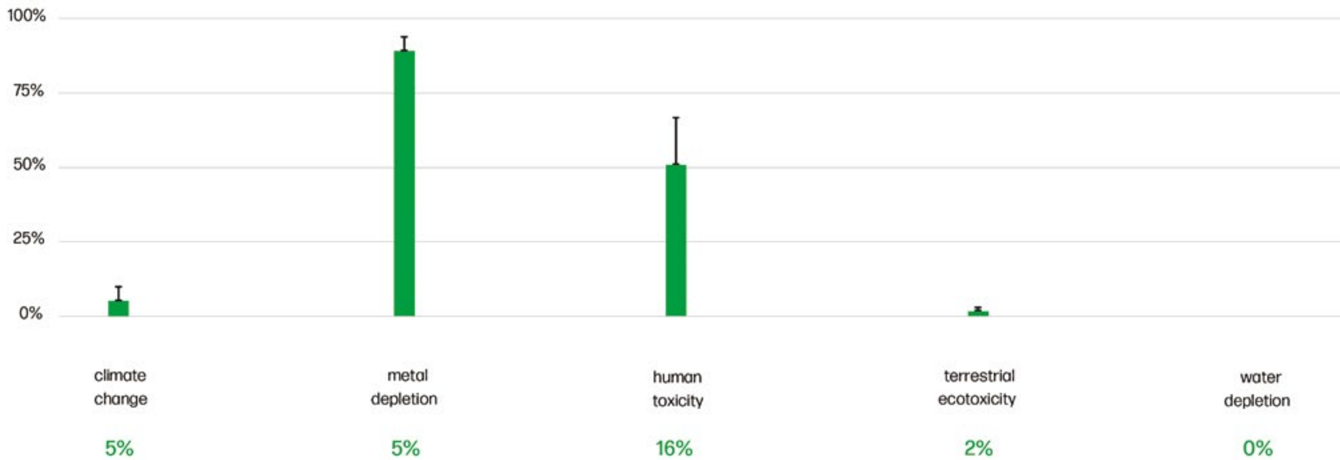

Figure 6: Outlay variation according to different production scenarios (data [4]; figure by the author).

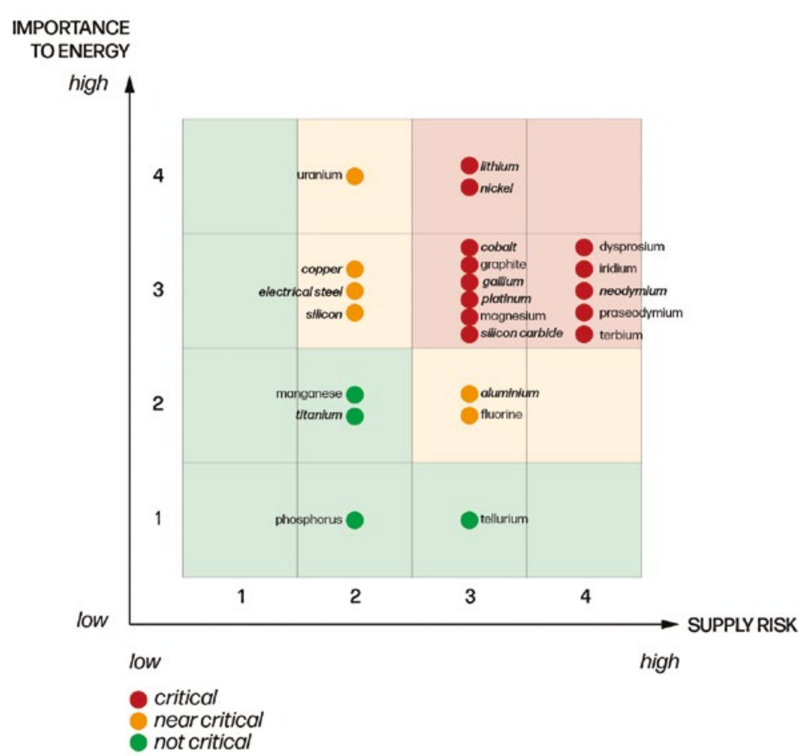

Figure 7: Supply risk table 2025-2035 [11].

new low impact materials - and downsides – higher impact set-ups –, as well as trade-offs which must be taken into account – higher fraction of the impacts for the system but an overall lower impact than alternative construction processes – of AM. This latter aspect raises the issue of favoring either the least damageable of two options or favoring a truly sustainable option - the thresholds are precisely designed to ensure the second approach, a need for guaranteeing more sustainable practices at large.

CONCLUSION

The present study discusses the sustainability of AM in AEC from a machinery perspective, demonstrating the importance of taking into consideration high-tech set-ups themselves to ensure an industrial development for the field that is compatible with environmental boundaries. It shows the ability of AM to navigate across a large range of impacts, and the possibility to choose amongst various set-ups and strategies to avoid the most damageable options. The study notably reveals the increases in impact associated with scaling up the systems and therefore the work area. Consequently, printing small is identified as a key development strategy for AM, privileging small-scale and low-impact set-ups that could also favor design for disassembly practices for 3D-printed component design.

Examining in greater detail the set-ups developed for component printing brings to light further choices. Gantries assessed here are designed for the end effector to travel across the printing bed, yet other options exist combining a static gantry with a moving bed. While only usable when manufacturing components, upon closer assessment such alternatives might reveal possibilities to limit exponential impacts and therefore represent venues of further development. In a larger perspective, considerations on on-site and off-site manufacturing bring to light issues of machinery design, and observations made in the present research on robotic morphology indicates that beyond AM strategies on construction scale themselves, complementary design directions exist for further research.

The study also offers methods of modelling production pathways as well as leads to further the study of impacts of AM in AEC, beyond the scale of the travel method employed. The matrix proposed might be extended with other criteria depending on the balance to be assessed, extended with other set-ups depending on the state of the art. The set of tools for production pathways modelling - outlays, end-of-life, thresholds - could be applied to set-ups identified in the matrix to understand their conditions of scale-up within environmental boundaries.

ACKNOWLEDGMENTS

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2. Building Realm

Additive Manufacturing for the building industry has matured. What started with bold promises, has turned out different than expected two decades later – for the good!

While the early generation of 3D-printing architects envisioned whole dwellings being erected in a single, yet comprehensive swipe of an almighty machine, reality gradually caught up with them. Others, from early on devoted their oeuvre to impressive machine-made designs and so reached a state of mannerism even before the technology was extensively explored. The visions of catching up on the degree of automation known from other sectors, i.e. automotive, are still more a dream than reality, but things are steadily moving forward.

Admittedly, today entire settlements [1] have been built using contour crafting [2]. Well, at least their walls. Process-inherent limitations did not yet allow for roofs or ceilings. This does not mean, that multi-story printed homes are impossible to build [3], one just must add some prefab-elements to balance processual shortcomings. And the finishing trades may not (yet) fear for their jobs – piping, wiring, flooring, etc. still remain manual labor.

Other representatives of the big-scale paste-extrusion use their sustainability for advertising. Using raw or refined local earth, remarkable adobe structures have been created [4,5], featuring a notable lower carbon footprint in comparison with their concrete cousins. Even the challenging task of creating a ceiling, respectively roof, has been solved through vaulting [6,7]. Undoubtedly, these clay-igloos represent a appealing examples of their kind, but their applicability on common housing concepts may be a subject of discussion. Again, all this was mostly limited to the building's structure and required manual finishing.

Besides residential projects, AM's capability to provide infrastructure was proven too, e.g. by MX3D's pedestrian bridge in Amsterdam [8]. Though its initial plan of onsite creation was not realized, the bridge soon became an object of great touristic interest. Unfortunately, having only a temporary building permission, it was recently dismantled and put in storage, waiting for a new purpose. A pity, if considered that such first-of-a-kind buildings are meant to be heritage-listed, not removed! To give AM Buildings a chance to keep their promise of providing simple and affordable construction, the support of the building authorities is indispensable.

So, building AM did not yet evolve into a deus ex machina, creating a turnkey home through the mere press of a button. It merely became another, indeed more automated, way to create (parts of) a building's structure. Time will tell, if it establishes further, as setting up the machines is criticized for requiring extra space, time and effort. But is this really so much more complex than putting up a construction crane and everything else we need for a conventional building site?

Aside from full-building AM, smaller components created through 3D-printing, also became an early subject of architect's interest. Digitally designed elements became a flagship in showing AM's capability to create unprecedented aesthetics. Often, their purpose merely lay in creating a contemporary ornament onto a common component. By creating a well-textured surface, companies like StudioRAP reimagined ceramic-cladded facades through 3DP [9,10] (Fig.1). Though any functions beyond aesthetics were rarely present in such projects, their supporting role for creating a social acceptance through design is undeniable.

After the enthusiasm of this first generation has faced confrontation with reality, nowadays researchers in building AM turn towards more functionally driven endeavors. Also, with full-scale AM being already market-available, the component level gained more attention in research. 3D Printing may not be perceived as disruptive as a decade ago, yet it did not lose its ability to inspire PhD students to envision novel applications. Today's projects focus much more on how to exploit AM's capabilities in creating application-oriented components, as showcased throughout the following pages.

Adding value beyond aesthetics appears to be the new goal in utilizing AM. For several use-cases, 3D-printing is still not able to compete with conventional processes in manufacturing. But does it even need to? Shouldn't it be better perceived as a complementary technology? May we use it to add functionalities to spotwise enhance the capability of already known systems?

The question "was this made through AM?" is contemporary. AM will, sooner or later, become just another common way of manufacturing architectural objects. When the hype is over, planners will not ask their contractors if a piece was casted, printed or milled – they will ask for its price, its functions or its longevity. We as researchers may enjoy being part of this hype, but also do our best to develop solutions to make AM a common thing that nobody is asking about anymore.

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TOWARDS A NEW GENERATION OF LATTICE STEEL STRUCTURES FABRICATED WITH WIRE-ARC ADDITIVE MANUFACTURING

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Metal Additive Manufacturing (AM), and in particular Wire-and-Arc Additive Manufacturing (WAAM), offers a promising solution to realize new sustainable and optimized steel structures. Lattice structures are characterized by high efficiency (in terms of high stiffness and minimized material use), however their application at the scale of the single element ("meso-scale"), such as beams and columns, is still hampered by the issue of the connection at nodes (in terms of geometry complexity, assembly and production cost). The ambition of this work is to propose a new class of efficient structural elements by exploiting the efficiency of lattice structures at the meso-scale through the adoption of WAAM production technology. The increased efficiency of lattice structures is provided by their high structural performances and reduced environmental impact, through the adoption of digital fabrication and optimization techniques for construction. The experimental tests were carried out on the single components of lattice elements: the single bars at different inclinations, the intersected bars and the elementary cells.

INTRODUCTION

The adoption of digital solutions for construction has proved to increase work safety and support the Circular Economy, by reducing the material waste and simplifying the resource recapture [1,2]. Additive Manufacturing (AM, or 3D printing) processes have the great advantage of flexibility in the geometry of the outcome. This aspect appears to be most suitable for the realization of efficient forms which are difficult to realize with conventional manufacturing techniques, such as rolling, casting, or milling, but result in a severe reduction in the material use. Such forms could be achieved with the use of novel Algorithm-Aided Design (AAD) tools, already commonly used in other industrial sectors, such as automotive and aerospace.

The application of both, AM solutions and computational design tools for steel structures have always been limited to few pioneering cases. Recent developments for AM processes in construction have seen the application of these techniques to realize a new generation of structures in concrete, polymers and metals [3,4]. Regarding applications in steel structures, the most developed metal AM technology (Powder-Bed Fusion, PBF) has often limited the maximum dimension of the printed outcomes. Thus, it has been adopted to realize ad-hoc connections parametrically designed either for structural optimization purposes

[5] or to create free-form gridshells [6]. However, due to the intrinsic geometrical constraints of the printer environment (enclosed in a box of typically 250-mm side), the application of PBF process is limited to the realization of small-size connections and structural details [7]. More recently, Directed-Energy Deposition (DED) techniques such as Wire-and-Arc Additive Manufacturing (WAAM) allowed to increase the dimension of the printed outcomes up to several meters of span, thus increasing the potential use of digital fabrication in steel construction [8]. The first application of this technique is the MX3D Bridge, the world's first steel 3D printed footbridge [9]. Recent research effort has been devoted to assess the structural behavior of WAAM-produced steel parts, such as tubular elements [10,11], gridshell columns [12], beams [13–16] and connections [17,18].

The computational design freedom of creating new structural forms was limited to the traditional building production which does not allow for such freedom. Hence, the application of computational design tools for free-form design was often limited to few explorations in pioneering architectural applications. With the advent of AM processes in construction, the use of structural optimization could potentially allow to realize a new generation of optimized structures [19]. Current research effort is paid to combine AM with optimization tools to solve issues related to manufacturing processes (such as overhang, see e.g.[20]) or exploit the material anisotropy to find new optimal solutions (see e.g. [15,21]).

WAAM FOR LATTICE STRUCTURES

WAAM-produced outcomes may be realized by adopting one of the currently known printing deposition strategies: (i) "continuous" printing, a layer-by-layer deposition, suitable to realize planar geometries, (ii) "dot-by-dot" printing, consisting in a droplet's deposition, suitable to realize bar-like elements, constituting the basic units of grid and lattice structures.

Currently, the interest in the "dot-by-dot" strategy is growing, allowing for the realization of structural elements, such as free-form gridshells, lattice structures and application of steel bars as reinforcement for innovative 3D-printed concrete structures [12,22]. Therefore, there is an increasing need in the assessment of the mechanical properties of WAAM-produced steel bars, which may differ from the typical behavior of conventionally-manufactured steel bars.

From the mechanical performances of the basic components (single bars and intersections) forming the WAAM lattice elements, it is possible to design a new class of steel structural elements by making use of computational design procedures and digital fabrication techniques. The final goal is to realize a new generation of green structural elements to reduce the environmental footprint of steel structures.

The first applications of WAAM lattice structural elements are specifically intended for vertical elements under either compressive loading or self-loading only, such as columns, pillars and poles. Various applications in Architecture, Engineering and Construction (AEC) are envisaged, among which: (i) aluminum pole systems for street lighting, (ii) stainless steel pillars for high architectural appealing buildings, (iii) carbon steel reinforcement grid for shotcrete 3D printed (SC3DP) free-form concrete systems (see e.g. [22]), (iv) carbon steel grid as retrofitting system for existing members (see e.g.[16]) (Figure 1).

In order to adopt algorithm-aided design techniques for WAAM and integrate structural design requirements for the construction industry, a new computational design protocol for WAAM lattice structural elements was developed. The computational design protocol combines: (i) specific features proper of WAAM process (such as manufacturing constraints, specific mechanical properties and geometrical tolerances), (ii) structural design requirements from Eurocodes based on the specific applications in Architecture, Engineering and Construction (AEC), and (iii) topology optimization algorithms for efficient designs. The protocol is based on new analytical derivation of efficient lattice poles based on slenderness and inertia equivalency currently under patent protection.

EXPERIMENTAL TESTS ON WAAM LATTICE COMPONENTS

The present section provides an overview of the main results of the experimental investigations carried out at University of Bologna. The aim is to study the mechanical response of "dot-by-dot" WAAM-produced stainless steel basic components of a WAAM lattice structure: (i) single bars at different inclinations, (ii) intersected bars and (iii) elementary cells (Figure 3). The influence of the build angle and nodal region on the mechanical response of the printed bars has been investigated by considering different build angles for both single and crossed bars, between the two limit cases of 0° and 30° build angles, corresponding to the limit conditions for printable structural applications. The mechanical response was studied under different loading conditions: tension, compression and bending [24]. The elementary cells were studied under compression loading by comparing different geometrical configurations, obtaining varying the cross-sectional geometry of the cell. The different experimental tests allow the assessment of the key mechanical properties of WAAM-produced lattice structures in construction applications. The mechanical tests were carried out on as-built specimens, hence not subjected to

Figure 1: Conceptual render of possible application of WAAM lattice columns [credits: Matilde Barchi, Sofia Capelli, Wessal Akrar].

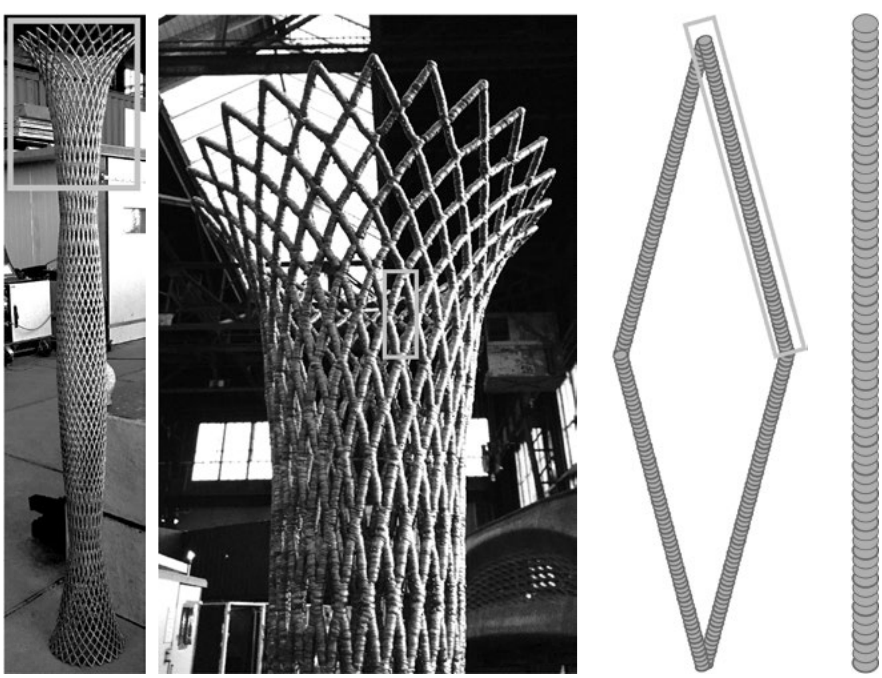

Figure 2: From the lattice column to the single bar.

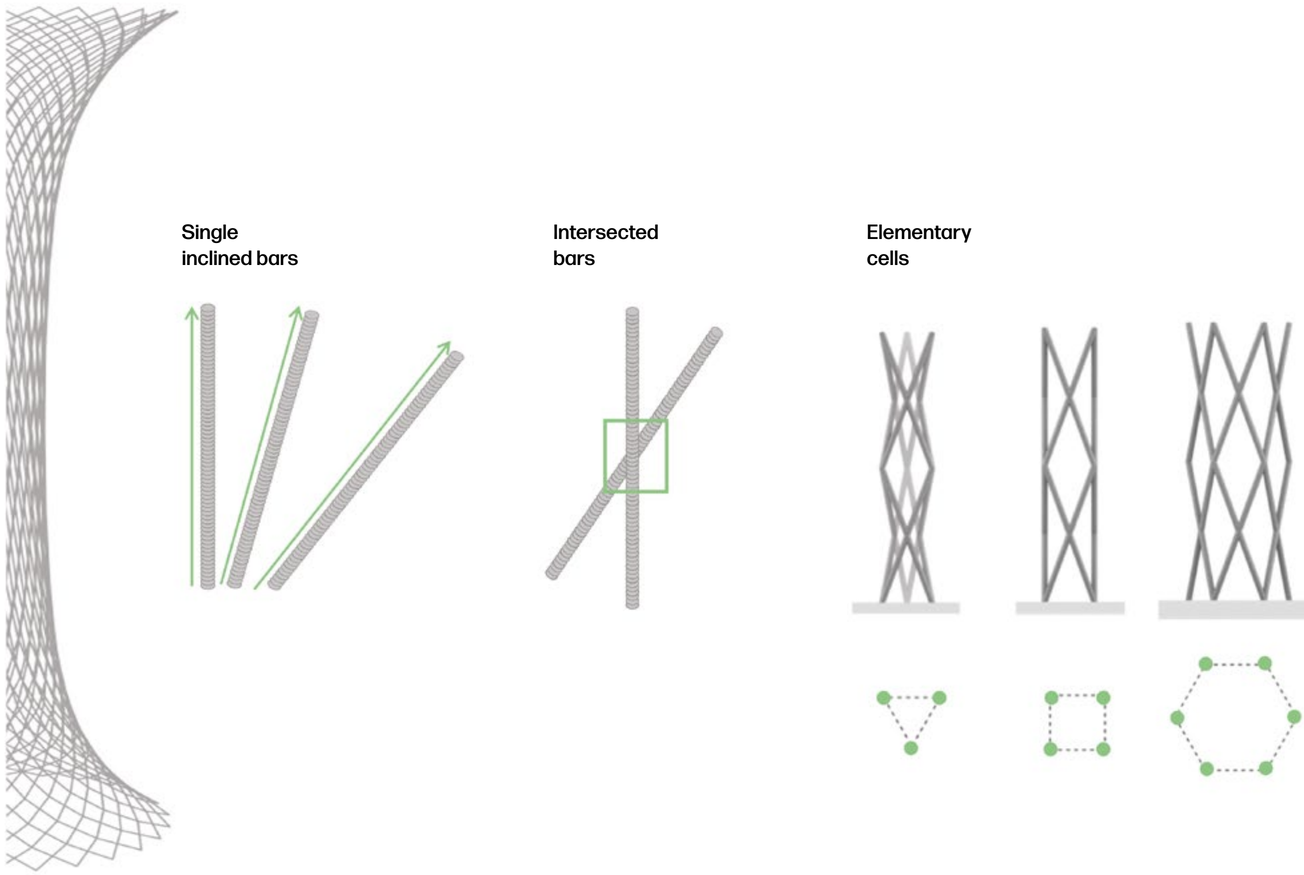

Figure 3: The basic components of WAAM lattice columns.

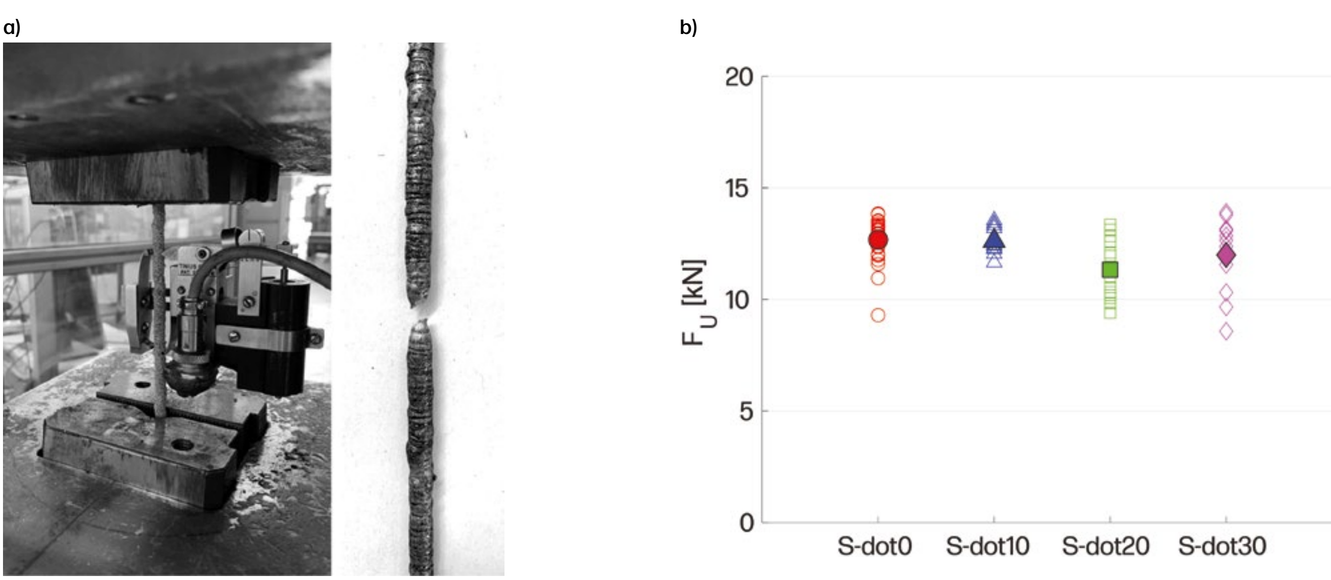

Figure 4: Tensile tests on single bars: (a) experimental set-up; (b) experimental results on single bars printed at different inclinations (from 0° to 30° build angle).

post-processing milling treatments, to account for the influence of the surface roughness and other geometrical irregularities, as for the case of real applications in construction.

SINGLE BARS

The single bars were tested in tension considering four different build angles: 0°, 10°, 20° and 30°. The tensile tests were performed at the Structural Engineering lab of the University of Bologna. The experimental set-up consisted of a Universal testing machine of 500 kN load capacity. The bars were tested in displacement control with a velocity corresponding to a stress rate of 2MPa/s. The strains were measured through a linear deformometer with a nominal dimension of 50 mm to detect the linear deformation of the rod up to yielding.

Figure 4 reports the values of ultimate tensile force (Fu in kN) comparing the results for the different build angles. It is possible to appreciate both the mean values for each batch as well as their dispersions. Overall, there is not a clear detrimental effect of the increasing build angle in the mechanical properties, as evidenced on previously-tested batches (see e.g. [26]).

INTERSECTED BARS

Crossed bars were produced with the same manufacturing set-up and process parameters as for the single bars, considering three different intersection angles (i.e. 10°, 20° and 30°). The aim of these tests is to investigate the detrimental effect of the presence of intersections, referred to as nodal regions, in the mechanical response under tensile loading. The three batches of WAAM-produced crossed bars with three different build angles were tested in tension to assess the influence of the nodal area and intersection angle (e.g. the build angle of the inclined bar, B) on the tensile behavior. For this aim, the crossed bars were manufactured in order to have one vertical bar, printed with a build angle of 0°, referred to as bar A, and one inclined bar printed at a certain build angle based on the different batch, referred to as bar B, with angles respectively of 10°, 20° and 30°.

The three batches are referred to as X10, X20, and X30, referring to crossed bars B printed at 10°, 20° and 30° build angle, respectively. For some specimens of each batch, a first series of tensile tests were performed by applying the tensile force on type-A bars, while a second series of tensile tests were performed on type-B bars. A total number of 43 WAAM-produced specimens were manufactured, 15 of type X10, 15 of type X20 and 13 of type X30. The tensile tests were performed using the same testing machine and the same loading condition of the single bars presented above.

Figure 5 reports the bar chart related to the ultimate tensile force (Fu) derived from the tensile tests performed on bars A and B of the three batches. The chart shows that, on average, the ultimate strength of both bars A and B decreases for increasing values of build angles, from an average value of 12.11 kN of bar A-X10 up to 8.40 kN of bar B-X30.

ELEMENTARY CELLS

The first studies on elementary cells were carried out in terms of numerical simulations to assess their overall behavior under compression loading.

Figure 6 presents the results from Finite Element Analysis (FEA) carried out through SAP2000 software on three different elementary cells, i.e. a triangular-based, a squared-based and an hexagonal-based cell respectively. The results confirm that the critical part of the elementary cells under compression loading is at the central nodes, while the whole behavior is mainly governed by bending moment.

These first outcomes suggest the need for further investigations on the influence of the geometrical configurations, in terms of both cross-sectional geometry and external shape, of WAAM lattice columns under various loading conditions. In particular, detailed analyses on the influence of the ideal vs real printed geometry of the lattice elements should be carried out, to calibrate the effective structural behavior of this new class of elements.

CONCLUSION

The application of metal Additive Manufacturing (AM) techniques for construction, and especially Wire-and-Arc Additive Manufacturing (WAAM), has proved to be a good solution towards a new generation of efficient and sustainable structural systems. Current research work has been focused on the application of WAAM to few pioneering projects, which also highlighted the need of proper design for manufacturing solutions to account for both the fabrication constraints and the specific mechanical behavior of the printed outcomes.

The present study aims at providing an integrated design approach to combine computational design with fabrication properties for a new class of resource-efficient WAAM elements. The approach is applied to new steel structural members which can be adopted either as columns or slender elements fabricated with WAAM dot-by-dot process. The presented approach aims for developing

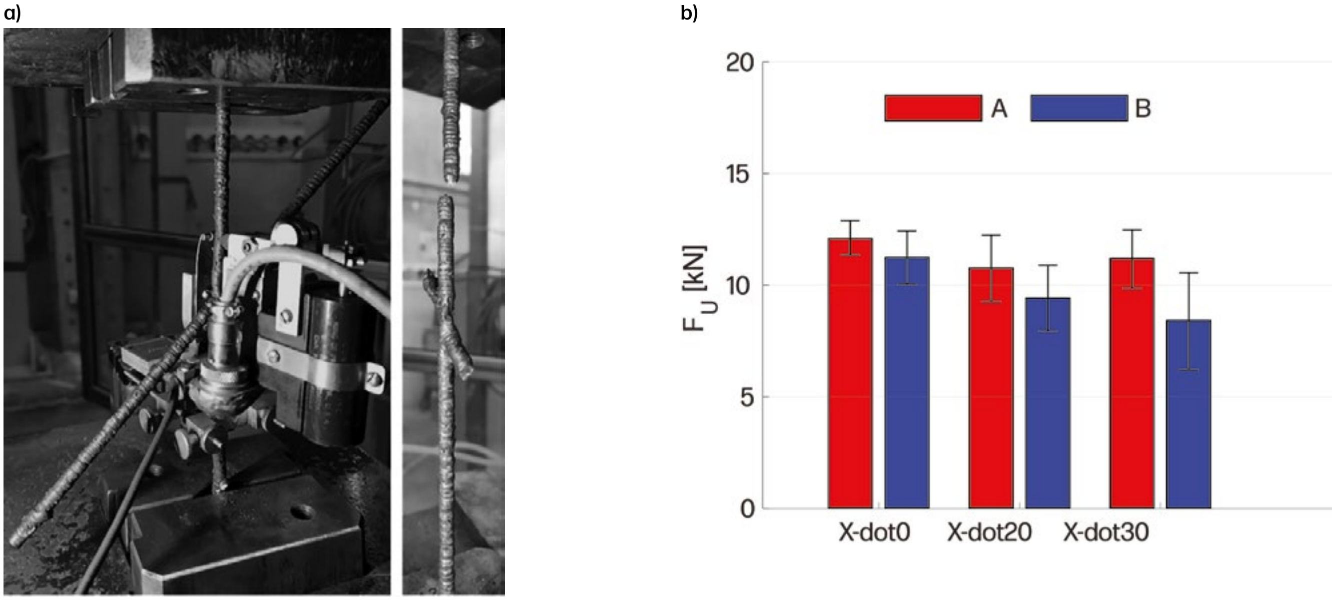

Figure 5: Tensile tests on intersected bars: (a) test set-up; (b) experimental results on intersected bars printed at different inclinations (from 10° to 30° build angle).

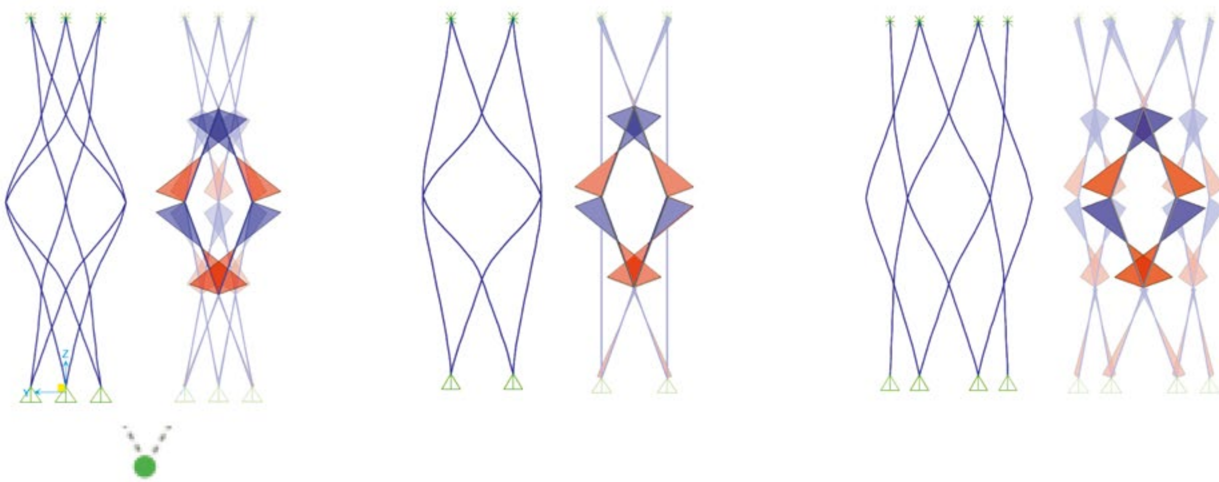

Figure 6: FEA results on the compression behavior of three elementary cells.

a new generation of resource-efficient structural elements, able to guarantee good structural performances while reducing the material use. Further considerations will be developed to assess the environmental and economic impact of WAAM production in construction.

ACKNOWLEDGEMENTS

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BRIDGING DIGITAL AND TRADITIONAL FABRICATION: ENHANCING PREFABRICATED METAL PANELS WITH ADDITIVE MANUFACTURING

Juan Ojeda
Alexander Wolf
Ulrich Knaack

Additive Manufacturing (AM) is distinguished as a stand-alone production method, however, integrating AM into established industries presents a key opportunity to accelerate the transition toward more advanced, adaptable, and efficient fabrication systems. In the Architecture, Engineering, and Construction (AEC) sector, particularly in the manufacturing of prefabricated metal panels, production still relies on traditional techniques such as rolling, stamping, bending, and cutting. These methods impose geometric constraints, generate material waste, and require costly molds and manual adjustments. As a result, large-scale production of identical parts becomes necessary, where the efficiency of the established setup is justified by the high volume of repetition. The absence of AM within these workflows limits innovation and adaptability, slowing the industry's evolution toward digital and automated production.

Integrating AM into existing fabrication workflows transforms metal panels from static, prefabricated components into adaptable, performance-driven elements that optimize structural behavior and material efficiency. Rather than replacing conventional manufacturing, AM serves as a complementary tool, selectively enhancing prefabricated components through targeted reinforcement, geometric modifications, and multi-material hybridization. Instead of fabricating entire structures, AM is applied precisely where needed without disrupting established production chains.

Advancements in computational workflows, real-time scanning, and robotic automation further enhance the feasibility of integrating AM within industrialized fabrication. By embedding AM into prefabricated panel manufacturing, the transition toward more efficient, flexible, and high-performance construction becomes achievable. Bridging the gap between digital fabrication and traditional manufacturing unlocks new possibilities for efficiency, sustainability, and even design-for-disassembly strategies. The challenge lies not only in refining AM technologies but in reshaping industrial workflows and mindsets to integrate them as essential tools within large-scale production.

INTRODUCTION

Additive Manufacturing (AM) has emerged as a transformative technology across various industries, enabling the production of complex geometries, reducing material waste [1], and introducing new design possibilities [2]. As AM moves beyond prototyping and into large-scale fabrication, its potential to complement existing manufacturing systems becomes increasingly relevant [3]. However, most AM processes remain stand-alone production methods, primarily used to fabricate on an isolated workflow rather than integrating with conventional processes. This presents an opportunity to rethink AM not as a substitute for traditional manufacturing, but as a complementary strategy that enhances prefabricated components and introduces new material efficiencies, as shown in an AI-conceptualized scenario in Figure 1, where robotic fabrication synergistically enhances metal panels through the integration of additional structures produced by additive manufacturing techniques.

Metal panels, widely used in architecture, structural applications, and industrial enclosures, rely on conventional forming techniques that prioritize mass production and standardized geometries. These methods remain constrained by fixed tooling, excessive material use, and the

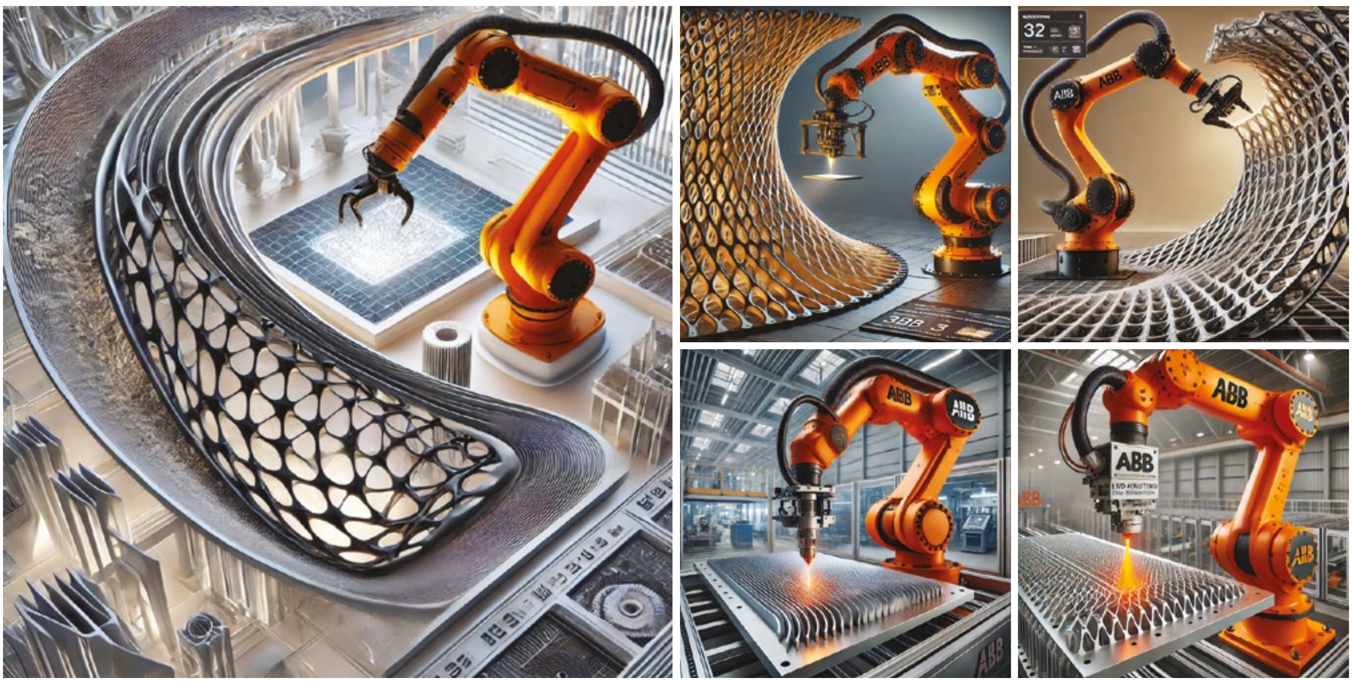

Figure 1: Conceptual AI visualization of robotic additive manufacturing reinforcing a freeform metal panel in an industrial environment. [OpenAI, 2024.]

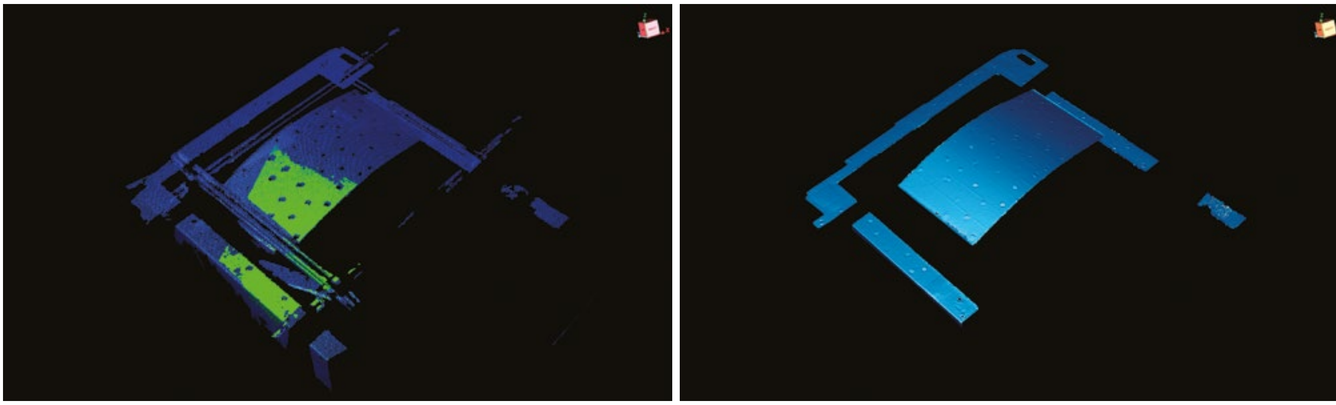

Figure 2: Sequence showing the process of using a 3D scanner to capture the geometry of a curved aluminum plate with scan markers (left), and the resulting mesh after post-processing and cleaning the point cloud (right).

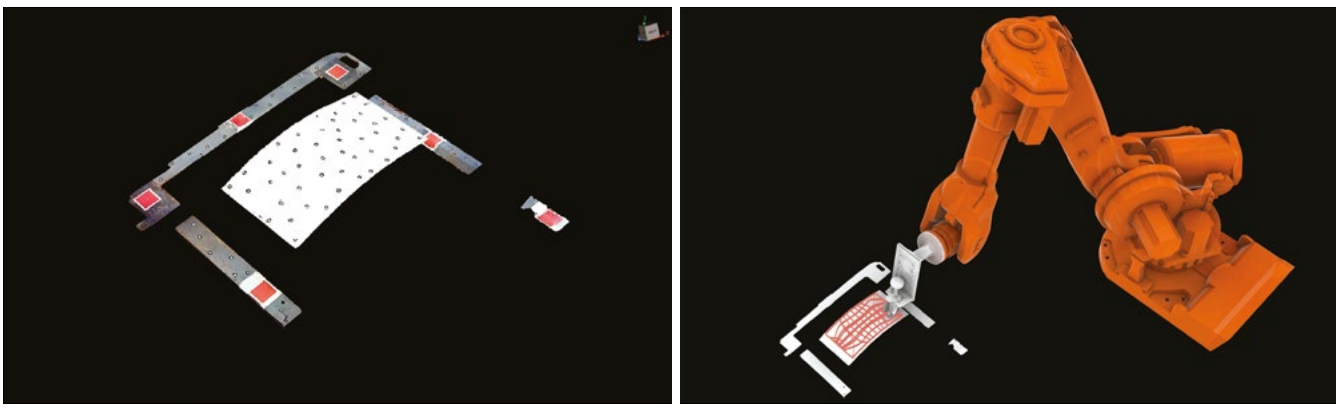

Figure 3: Texturized 3D mesh generated from the point cloud. Markers enable scanning reflective surfaces (left) and positioning the model relative to the robot's workspace (right).

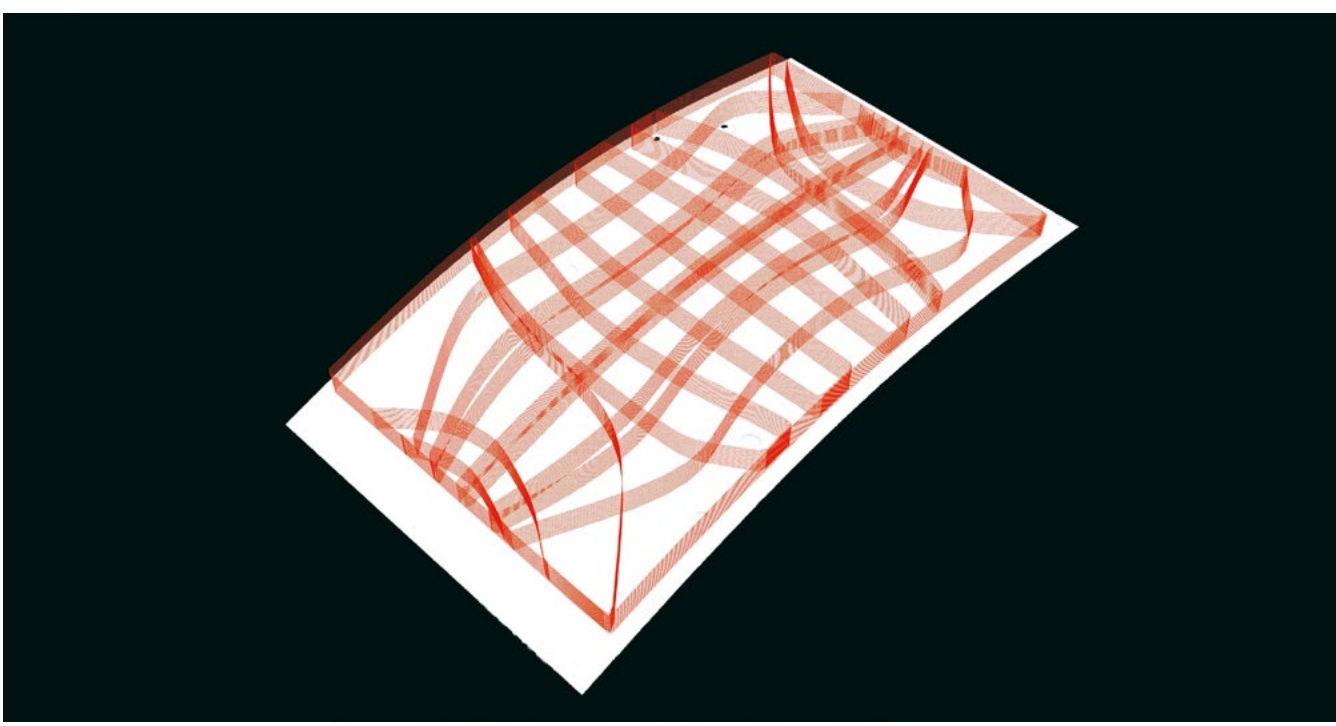

Figure 4: Example of a printing path of 20 layers, each 1 mm thick, over the aluminum surface.

high cost of molds, particularly when applied to complex freeform geometries. AM introduces a paradigm shift by treating prefabricated panels as adaptive substrates that can be selectively reinforced, modified, or optimized for specific performance criteria. Rather than requiring dedicated tooling for every geometric variation, AM enables a more flexible and dynamic approach, responding to material and structural requirements in real-time.

Despite these advantages, integrating AM into industrialized fabrication introduces technical challenges, particularly in geometry acquisition (Figure 2), process control, thermal management, and multi-material integration, among others. For example, when capturing the geometry of non-planar aluminum panels, advanced 3D scanning methods are used to generate detailed point clouds that accurately capture the surface geometry despite its reflective properties. These point clouds are subsequently processed into 3D meshes, which can be enhanced either by applying textures derived from the scanner's captured images or by applying color information directly from the point data (Figure 3). Additional computational steps are necessary to align the reconstructed mesh with the robot's working plane, allowing additive manufacturing paths to be precisely projected and adapted to the complex geometries of prefabricated components (Figure 4). Addressing these barriers is key to bridging the gap between digital fabrication and traditional metal forming, unlocking AM full potential as a scalable, performance-driven enhancement tool. By leveraging computational design workflows, robotic automation, and real-time scanning, AM offers a material-efficient alternative to conventional manufacture strategies. This integration represents a step toward a more adaptable, sustainable, and scalable approach to panel fabrication, aligning with the evolving demands of architectural and structural applications.

TRADITIONAL METAL PANEL FABRICATION AND ITS LIMITATIONS

The production of metal panels for architectural and structural applications relies on well-established forming techniques, each optimized for mass production but often inefficient when applied to customized or freeform designs. These panels generally fall into two primary categories, composite and monolithic panels, each follows different fabrication processes, facing design, cost, and material efficiency constraints. A common approach to achieving freeform facades while minimizing manufacturing complexity and cost is the triangulation of panels (Figure 5). By subdividing a curved surface into a series of flat triangular segments, fabricators can rely on standard cutting, bending, and assembly processes rather than expensive molds or complex double-curved forming techniques [4]. While this method reduces production costs and simplifies installation, it increases the number of individual components, leading to higher material waste, additional joints, and a fragmented visual appearance that may compromise the original design intent.

COMPOSITE METAL PANELS

Composite metal panels, widely used in building facades and lightweight enclosures [5], consist of thin metallic skins bonded to a core material such as aluminum honeycomb, polyethylene, or fire-resistant mineral cores. Their production process typically includes:

- Coil coating: metal sheets are pre-treated with protective and aesthetic finishes.
- Lamination: the metal skins are bonded to the core through adhesives, pressure bonding, or heat fusion.
- Cutting and shaping panels are resized and prepared for final installation.

While these panels achieve an excellent strength-to-weight ratio, they lack geometric flexibility. The rigid core structure makes it difficult to accommodate double-curved or freeform surfaces, leading to the common practice of faceting, where curved geometries are broken down into small, flat triangular segments for approximation [6] This increases material use, complicates assembly, and restricts the potential for continuous, structurally efficient panelization.

MONOLITHIC METAL PANELS

Monolithic metal panels, used in structural reinforcements, industrial enclosures, and roofing systems, are fabricated through bulk metal forming techniques such as:

- Rolling: produces continuous metal sheets of uniform thickness, ideal for flat and corrugated panel designs.
- Stamping (Figure 6) and deep drawing: uses rigid dies to shape panels into predefined forms, offering efficiency in high-volume production but at the cost of expensive molds and limited geometric flexibility [7].
- Incremental Sheet Forming (ISF) (Figure 7): a CNC-controlled process that deforms sheets incrementally, allowing for customized three-dimensional geometries without the need for dedicated molds [8] However, ISF remains constrained by process speed, thickness limitations, and challenges in achieving precise surface quality.

Both composite and monolithic panels require significant material use, particularly when structural stiffness needs to be improved. Traditional fabrication methods typically achieve this by increasing the material thickness uniformly or by relying on mechanical stiffeners, which require additional assembly and fastening.

This lack of localized reinforcement leads to material inefficiencies and limits structural optimization. Additionally, traditional forming techniques depend heavily on fixed molds and manual labor, restricting design freedom, scalability, and adaptability in highly customized projects [9].

As the demand for lightweight, geometrically complex, and material efficient solutions increases, these traditional manufacturing processes are struggling to keep pace. The reliance on standardized thicknesses, inefficient material distribution, and high setup costs highlights the need for a hybrid fabrication approach. One that combines precision, flexibility, and sustainability through computational and digital manufacturing strategies.

ADDITIVE MANUFACTURING AS AN ENHANCEMENT STRATEGY

Rather than replacing traditional manufacturing, AM provides an adaptive reinforcement method, transforming prefabricated metal panels into structurally optimized components [10]. Unlike conventional approaches that require uniform thickness increases or additional mechanical stiffeners, AM enables localized reinforcement and geometric modifications directly onto existing panels. This allows manufacturers to enhance performance without disrupting base fabrication processes, making AM a scalable enhancement tool rather than a disruptive alternative.

LOCALIZED MATERIAL DEPOSITION FOR STRUCTURAL REINFORCEMENT

One of AM key advantages is its ability to deposit material selectively, reinforcing only high-stress regions rather than applying uniform stiffening [11]. This technique, particularly useful for thin sheet applications, enables:

- Load-responsive reinforcements, where material is added in structurally necessary locations rather than across an entire panel.
- Anisotropic stiffness distribution, optimizing mechanical properties without excessive weight gain.
- Multi-material integration, allowing for metallic, polymeric, or composite reinforcement strategies based on specific functional requirements.

COMPUTATIONAL WORKFLOWS AND DIGITAL MANUFACTURING

AM's integration into industrialized fabrication relies on advanced computational workflows that enhance precision and adaptability. By leveraging Finite Element Analysis (FEA) and real-time scanning, reinforcement strategies can be dynamically adjusted to match specific stress distributions and fabrication tolerances (Figure 8). Key computational methods include:

The creation of a real-time virtual model of prefabricated panels enables precise geometry mapping, structural analysis, and process optimization [12]. This dynamic representation allows for continuous monitoring, simulation, and predictive analysis, ensuring fabrication adjustments can be made before physical production, reducing errors and improving material efficiency.

Digital Shadow: A high-resolution reconstruction of a 3D model that captures the current state of a prefabricated panel and serves as a basic reference for future workflow steps. Unlike a full digital twin that is continuously updated with live data, the digital shadow represents a static yet highly detailed snapshot of the geometry, enabling accurate pre-processing, path planning and robotic motion control before applying AM reinforcement. [13].

Parametric Optimization: applying algorithm-driven reinforcement placement based on load path analysis.

AI-Driven Process Control: adapting material deposition rates and toolpath generation in response to fabrication deviations.

EXPANDING THE POTENTIAL OF AM IN PREFABRICATION

Hybrid AM approaches introduce a new layer of design adaptability and performance optimization within prefabrication. Instead of producing fully 3D-printed components, AM techniques can be used to:

- Enhance existing structural elements, reducing material waste and excess mass (Figure 9).
- Integrate smart features, such as embedded sensors, thermal control layers, or acoustic insulation.
- Facilitate design for disassembly, enabling panel systems to be recyclable, reconfigurable, and adaptable over the long term.

Figure 5: Massimiliano and Doriana Fuksas (2007-2012). Georges-Freche School of Hotel Management. Montpellier, France.

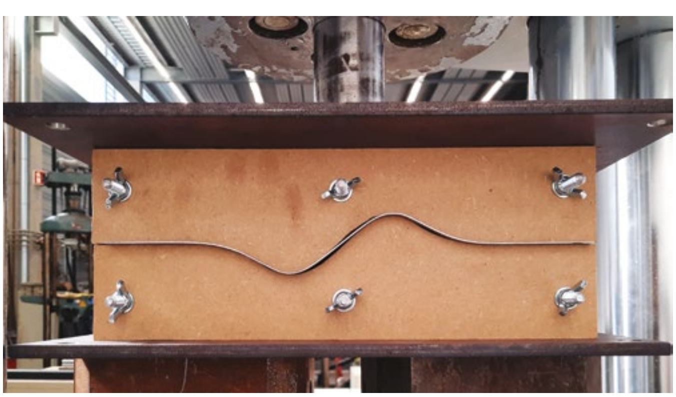

Figure 6: MDF dies for forming a 1mm steel plate. The stamping process requires a die design with a shape different from the desired part due to the spring back that occurs when the plate is released after deformation.

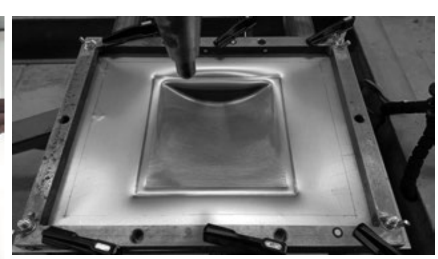

Figure 7: Robotic arm shaping a 0.4mm steel plate with Single Incremental Forming.

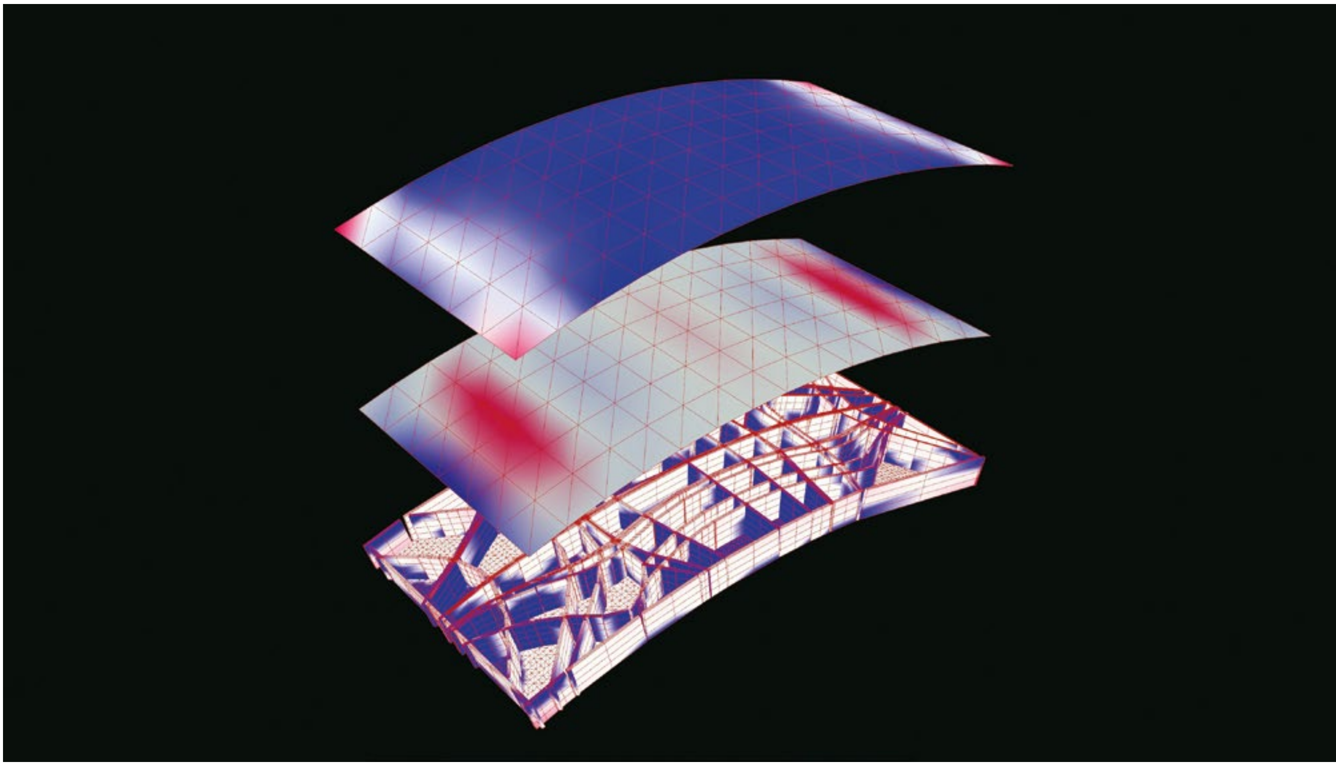

Figure 8: Using Karamba3D to analyze the stress lines used as guides to create 3D printed reinforcements, adding material in the most needed areas to reduce the overall thickness of the sheet that serves as the substrate.

Figure 9: 1 mm steel plate reinforced with 4 ribs of 6 layers of 0.95 mm printed with WAAM. The reinforcement in turn generates the plastic deformation of the plate which follows a unidirectional curve with a radius of approximately 4 meters.

BRIDGING THE GAP BETWEEN TRADITIONAL AND DIGITAL FABRICATION

The integration of AM into panel manufacturing represents a critical shift in industrialized construction. One that balances customization with production efficiency. As robotic automation and multi-material printing techniques continue to evolve, the potential for digitally augmented, performance-based fabrication becomes increasingly viable. AM offers an unprecedented level of precision, adaptability, and sustainability, ensuring that future architectural and structural systems are optimized for both form and function.

DISCUSSION

Technical Challenges in AM-Enhanced Panels

The integration of AM into prefabricated metal panel fabrication presents a technical challenge that extends beyond material deposition. Unlike traditional forming processes, which operate within well-defined mechanical behaviors and predictable tolerances, AM introduces thermal distortions, variable deposition rates, and material inconsistencies, complicating its seamless integration into industrial workflows.

One of the main obstacles in hybrid AM manufacturing is geometric accuracy and surface adaptation. Prefabricated metal panels formed by rolling, bending, stamping, or incremental forming, often have geometric deviations that must be addressed before AM can be applied. Real-time scanning and digital reconstruction are required to create an accurate 3D model of the existing surface. However, current scanning techniques have limitations in terms of time-resolution-post-processing, surface reflectivity, and computational processing speed, which affect the automation of the processes. Advances in machine vision, sensors, and adaptive path planning for robotic AM systems are needed to improve accuracy and efficiency.

Another critical technical challenge is thermal distortion and residual stress accumulation, particularly in metallic AM processes such as Wire Arc Additive Manufacturing (WAAM). Unlike traditional panel stiffening methods, that rely on mechanical deformation, WAAM deposits molten material layer by layer, leading to localized heating, cooling, and shrinkage effects. These inconsistencies can induce warping and internal stresses, making it difficult to achieve predictable mechanical properties. Current strategies, including preheating, interpass temperature control, path planning, and computational heat dissipation simulations, provide partial solutions but require further refinement for large-scale industrial use.

Thermoplastic-based reinforcements, such as Fused Deposition Modeling (FDM), face challenges in material adhesion and anisotropic performance. Unlike metallic bonding, where fusion occurs through melting, polymer-to-metal adhesion depends on surface treatment, chemical bonding agents, or mechanical interlocking. Ensuring long-term durability in outdoor applications remains an open question, as UV radiation, humidity, and temperature fluctuations that can degrade polymer inserts. Additionally, anisotropic material behavior in fiber-reinforced polymers must be carefully controlled to ensure structural reliability.

INDUSTRIAL INTEGRATION CHALLENGES

From an industrial perspective, AM integration faces challenges in scalability and production efficiency. Traditional panel production lines are designed for high-repetitive manufacturing, where each unit follows a fixed sequence of operations. AM, by contrast, introduces non-uniform material additions, requiring real-time process adjustments, making it difficult to integrate into automated production lines. Current robotic AM processes lack the speed and consistency required to match traditional manufacturing flow, making AM-enhanced panels more suitable for custom, high-performance applications rather than mass production.

Another critical barrier to widespread adoption is cost effectiveness. While AM offers material savings through localized reinforcement, it requires high-precision robotic systems, highly skilled operators [14], specialized deposition equipment, and computational infrastructure, all of which contribute to higher initial investment costs. The return on investment (ROI) for AM-enhanced manufacturing remains highly application-specific, favoring industries with high-performance demands (such as aerospace, advanced facade systems, and lightweight structural elements) rather than low-cost, high-volume manufacturing sectors. In addition, standardization and regulatory challenges present a major obstacle. Traditional prefabricated panels conform to established building codes and material performance standards, while AM-based reinforcements introduce new mechanical behaviors, bonding mechanisms, and failure modes that require rigorous validation. The lack of industry-wide standards creates hesitation in large-scale adoption, as manufacturers lack clear guidelines for quality control, testing, and certification of AM-enhanced products.

Despite these challenges, ongoing advances in real-time scanning, robotic automation, and computational design continue to improve the feasibility of AM integration. Addressing these technical and industrial barriers is essential for AM to transition from experimental workflows to standardized, scalable manufacturing techniques.

CONCLUSION

The use of AM in the production of prefabricated panels represents a fundamental shift in industrialized construction and material optimization. Rather than replacing traditional forming techniques, AM serves as a targeted reinforcement strategy, that enhances mechanical properties while maintaining compatibility with existing workflows. Hybrid approaches introduce performance-driven modifications, localized stiffening, and adaptive material distribution, to achieve structural efficiencies not possible with conventional methods.

Despite its technological promise, several barriers must be addressed to ensure scalability, economic feasibility, and regulatory acceptance. Overcoming thermal distortions, optimizing adhesion mechanisms, and implementing real-time process control will be critical for refining AM-enhanced panel fabrication for widespread industrial adoption. Furthermore, the cost-benefit ratio of AM integration requires deeper analysis, particularly in comparison to conventional reinforcement strategies. Future research should focus on multi-material hybridization, combining metallic and polymeric reinforcements within a single prefabricated panel. By integrating computational simulation, AI-driven process optimization, and sensor-based feedback loops, AM-enhanced fabrication could evolve into a fully adaptive, real-time controlled system, exceeding the static nature of manufacturing methods.

Beyond technical development, collaborative efforts between researchers, industry stakeholders, and regulatory bodies will be essential for establishing standardized guidelines for AM-enhanced panels. Developing certification protocols and defining clear performance benchmarks will accelerate industrial acceptance and enable scalable deployment across sectors such as architecture and advanced engineering applications.

Embedding AM within industrialized fabrication workflows represents a significant step toward a digitally integrated, high-performance, and resource-efficient manufacturing paradigm. This transition not only enhances structural optimization and sustainability but also paves the way for new material innovations, adaptive manufacturing systems, and intelligent fabrication strategies that will redefine the built environment.

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FIGURES

1. Conceptual AI visualization of robotic additive manufacturing reinforcing a freeform metal panel in an industrial environment. Prompt: *A robotic arm using additive manufacturing to reinforce a freeform metal panel in an advanced industrial setting. The robotic arm features a 3D printing nozzle end effector, precisely extruding filament onto the panel to enhance its structural integrity. The background showcases an industrial workspace equipped with metal panels, high-tech fabrication equipment, and digital monitoring interfaces. The scene emphasizes precision engineering, automation, and the seamless integration of AM technology into metal panel fabrication* [OpenAI, 2024.]
2. Sequence showing the process of using a 3D scanner to capture the geometry of a curved aluminum plate with scan markers (left), and the resulting mesh after post-processing and cleaning the point cloud (right).
3. Texturized 3D mesh generated from the point cloud. Markers enable scanning reflective surfaces (left) and positioning the model relative to the robot's workspace (right).
4. Example of a printing path of 20 layers, each 1 mm thick, over the aluminum surface.
5. Massimiliano and Doriana Fuksas (2007-2012). Georges-Freche School of Hotel Management. Montpellier, France. Redrawn by the Authors 2025
6. MDF dies for forming a 1mm steel plate. The stamping process requires a die design with a shape different from the desired part due to the spring back that occurs when the plate is released after deformation.
7. Robotic arm shaping a 0.4mm steel plate with Single Incremental Forming.
8. Using Karamba3D to analyze the stress lines used as guides to create 3D printed reinforcements, adding material in the most needed areas to reduce the overall thickness of the sheet that serves as the substrate.
9. 1 mm steel plate reinforced with 4 ribs of 6 layers of 0.95 mm printed with WAAM. The reinforcement in turn generates the plastic deformation of the plate which follows a unidirectional curve with a radius of approximately 4 meters.

FUNCTIONALIZED BRICKS: ADDING VALUE TO BUILDING CERAMICS THROUGH ADDITIVE MANUFACTURING

Alexander Wolf
Ulrich Knaack

Contrary to several other AM (Additive Manufacturing) technologies, the 3D Printing of ceramics is not suited for architectural on-site production. Mainly limited by the crucial necessity of a subsequent firing process, this technology may only be used in workshop conditions. Nevertheless, ceramics have a high relevance, as well as a rich history among building materials. This chapter presents suitable application cases in the field of tension between a new technology and a traditional material.

INTRODUCTION

Looking at the use of ceramics in building construction, it is noticeable that components made from fired clay do not only prove their versatility through a broad range of applications, but also through their long history of utilization. In the 5th Millenium BC, ancient Babylonians noticed how firing dried clay bricks rendered them into ceramics, making them more resilient to loads and environmental influences [1]. As this knowledge spread, new applications emerged, including rooftiles, pipes, and glazed tiles - each making use of the material's favorable properties in their own way (Figure 1). In particular the fact, that clay is easy to put into almost any shape while moist allows for such a wide variety of utilization.

Along with the industrialization in the 19th century, inventions like the extrusion process and Hoffmann's Kiln [2] led to higher yields and made ceramic bricks a main building material in Europe's cities at the *fin de siècle*. Though in the early and mid 1900's competing materials such as aerated concrete or calcium-silicate appeared, ceramic bricks still hold about 1/3 of market share for residential buildings in Germany [3]. Same is for other applications: even though rooftiles from cast concrete or bathroom objects enamelled metal or PMMA (Polymethyl methacrylate) are available, none of them yet was able to force their ceramic counterparts out of the market.

While geometrically more simple-shaped are traditionally created in an extrusion process, complex objects

Figure 1: The versatile use of ceramic components in a facade. Klinker Bricks alongside glazed tiles and rooftiles, as well as ornaments such as pinnacles. (Hospital de la Santa Creu i Sant Pau, Barcelona, Spain).

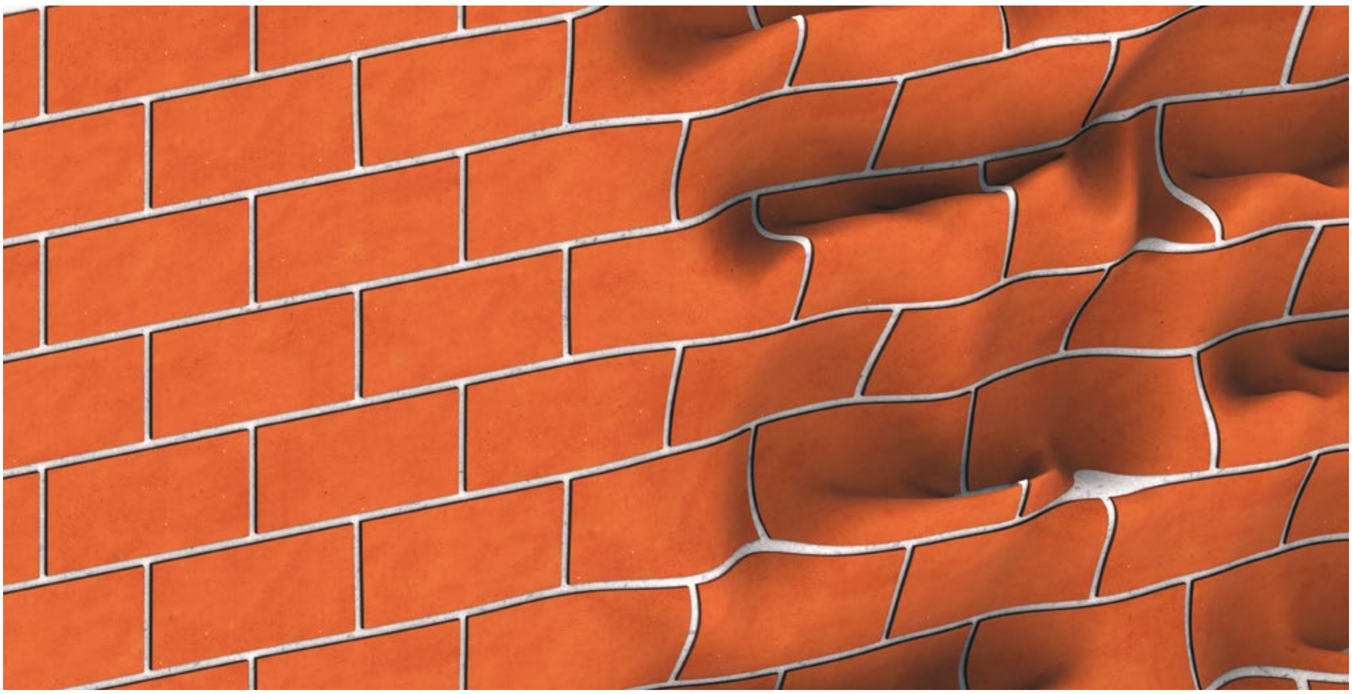

Figure 2: Transition from a planar surface to an undulating one.

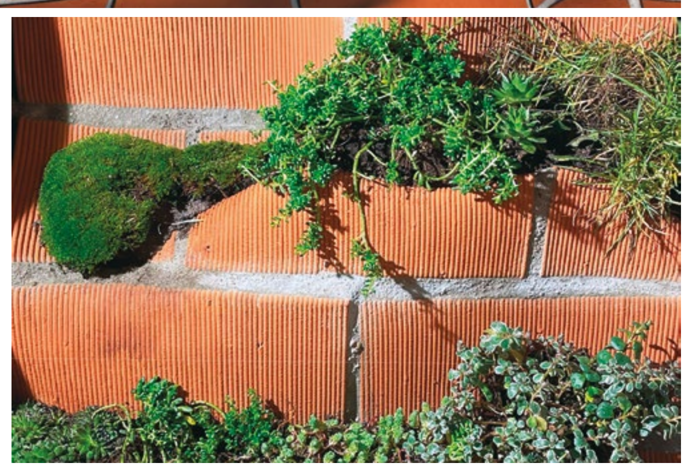

Figure 3: Greened façade hosting undemanding plants. Note the vertical layer artifacts in the bricks.

such as sinks are cast into gypsum formwork using a more viscous clay-slurry [4]. Along with the rise of AM since it's early steps in the 1980s [5], along with a variety of other materials, methods to 3D print ceramics came up. Though there is a broad field of different technologies to do so [6], only Robocasting [7] appears capable of creating objects in the size needed for architectural applications [8]. In this extrusion-based process, a geometry is built up line-by-line and layer by layer. Though this technology comes along with several challenges, as discussed in an earlier Volume of AM Perspectives [4], a multitude of projects has already been carried out [9]. By overcoming some of the aforementioned challenges through research [10,11], now the way appears paved for an industrial implementation [12].

APPLICATION CASES

While AM technologies for other materials, such as steel [13,14] concrete [15] or (unfired) clay [16,17], are well suited for the in-situ production of whole buildings, the AM of ceramic objects lacks this ability. This is mainly due to the crucial necessity of firing the pieces to render dried clay into ceramics at about 1.000-1.200°C, depending on the desired properties of the final material. As this usually takes place in large tunnel kilns, production can only take place at industrial facilities.

Further, being limited to sizes of about 50 x 50 x 50cm, due to limitations while shaping, as well as distortions during drying and/or firing, ceramics crafted through AM may rather be perceived as medium-sized components, than as large-scale modules such as walls.

In addition, their production is very time-consuming. While a stone can be formed in just 3 seconds in the conventional extrusion process, robocasting requires almost 50 minutes to produce a comparable geometry [12], assuming a low printing resolution. Given these preconditions, from an economical point of view, it is advised to use 3D printed ceramic components mainly as a supplementary in combination with conventionally manufactured components [18].

Looking at projects carried out in this field, it is noticeable that many of them merely made use to create ornamental shapes, rather than to add functionalities beyond aesthetics [9]. Furthermore, the use of AM ceramics in a complementary manner was only executed in only one of the reviewed projects [19], in this case, however, again without any specific functionalization.

The following sub-sections present several projects using AM in order to functionalize ceramic building components. All projects were carried out using Robocasting with respect to the aforementioned prerequisites.

GREEN KLINKERS

This research was carried out in an attempt to include façade-greening into double shell masonry made from facing bricks [20]. Using generative algorithms, undulating surfaces were generated, featuring pockets able to hold substrate for greening. The system is able to be integrated into common double-shell brickwork's outer layer by smoothly transitioning from the planar surface into the undulating one (Figure 2). This takes place with respect to the format of the bricks, as well as the bond in which they are arranged.

Since only bricks fired at high temperatures possess the favourable properties for use in facing masonry, the special shaped components were fired at 1.150°C. As their geometry partially provided steep overhangs, it was decided to manufacture them turned 90° to avoid the use of support structures, as well as to create their curvature in better detail. This led to the result, that the layered appearance, characteristic for many 3D printing processes, in this case appears as vertical lines on the surface (Figure 3). As strategies to overcome such had not been researched at the time this project was carried out, the surface of these special components does noticeably differ from conventional brick's surfaces. Nevertheless, it can be stated that most of the post-processing methods for surfaces found later [11] are applicable, making harmonized appearances now feasible.

For greening the façade, the grooves in the undulating surface were filled with substrate first. Then, a variety of undemanding crops, such as *Sedum, Sempervivum, Dianthus Petraeus, Achillea collina, etc.* were planted into these (Figure 3). Most of these plants are common in greened roof systems and known for their undemanding nature. This happened in the expectation to so create a low-maintenance system, which may only receive its water through outside weather conditions.

After production, the 50 x 50 cm demonstrator was monitored for seven weeks to assess the plants accrual and condition. Though from the 15 plants used, most adapted rather well, unfortunately 3 did not survive the experiment. Nonetheless, the study was perceived as generally successful, even though for another iteration certain adaptations may be advised.

Looking at the functionalization aspects this article focuses on, several aspects can be concluded for Green Klinkers. First, from the perspective of geometry, the project included a low-tech kind of functionalization merely through an articulate and complex geometry. Secondly, from the production aspect, no approaches to overcome the aforementioned limitations of the Robocasting process have been undertaken. Finally, a complementary use of specially shaped components can somewhat be recognized, as planar bricks fade over to undulating ones. However, to achieve a greened façade, even if only partly, a greater number of AM Components is required, leading to high efforts in production and the resulting costs.

THE NESTING BRICK

Dealing with an already market-available product, this project focussed the digitalization of a yet manual process to shape specialized bricks. Hagemeister GmbH, a German brick manufacturer, provides several types of hollow ceramic elements serving as nesting-opportunities for endangered species, that flushly blend in common masonry façades (Figure 4). However, their production is still carried out in a fully manual process by one artisan craftsman. This not only leads to high unit-prices and a production capability much lower than the request for the project. It also puts at risk the long-term availability of such products as the skilled craftsmen for such products went almost extinct.

In an approach to digitalize the production of this highly specialized components, first the manufacturer provided digital Models of some of their products. To assess their usability for AM and to identify challenges in their production, these were sliced and printed without much prior reflection. This attempt clearly revealed several challenges of the idea of a "straight digitalization", such as unreasonable long printing paths, which in turn led to long processing times. Also, some geometrical features had to be altered, in order to not fall victim to the printer's low resolution. Further, overhanging and bridging areas required support material, which was also required in several cases to prevent distortion and cracking during drying and firing. Lastly the layer-artifacts in the surface prevented their integration into commonly produced masonry.

To overcome this, several optimizations have been carried out. First of all, a favourable setting for strand-width and layer height was determined. Then, the geometry was rebuilt with respect to the dimensional system given by these two parameters. Also, geometries were re-oriented to minimize overhang and bridging areas, though in some regions additional support structures were still required to enable production. Following the printing, facing surfaces were processed in order to achieve a more harmonized appearance in comparison with commercial bricks. Lastly, after firing at 1.200°C, anti-distortion-supports were cut out and all pieces were assembled into a demonstrator (Figure 4).

On the end of this iterative process, a time-saving of 15% on average was achieved, while in general processability was enhanced. Figure 5 provides a direct comparison of the first and iteration of a Nesting Brick, which is suitable as a habitat for bats. Overall, the study was perceived as successful, as the digitalization of a yet manual process through AM was achieved. Nevertheless, prior to a transfer of this methodology into an industrial context, several adjustments are advised [12].

In view of functionalization, the Nesting Brick again provides a low-tech functionality, but this time through a non-complex geometry. In terms of production, the transfer from an artisan manual process to a digitalized one represented the challenge of the project. This succeeded primarily through a "redesign for additive manufacturing", going hand in hand with applying findings from other research [10,11]. With a view to the economical use of AM ceramics in a complementary way, the Nesting Brick appears much more efficient in adding value through functionalization to a brick wall compared to the aforementioned greened façade, as less components are required to achieve this.

HERITAGE-BRICKS

Throughout this still ongoing research, it is envisioned to use AM Ceramics in order to replace broken or missing pieces in historic buildings. The scope of application for this ranges from creating rather low-detailed profiled bricks, over to reprint complex ornaments such as the glazed pinnacles seen in Figure 1. Due to their rich history, ceramic components occur in a multitude of historic buildings. With their maintenance, not only cultural heritage is preserved for future generations, but also sustainability is granted through their long-term use. Nonetheless, this is perceived only as a technology and how far to go with such replacement-methodologies may be decided by building history experts in each individual case.

Starting with geometrically low-complex parts, profiled bricks have been printed, mimicking existing components as used in cornices, lintels or pilasters (Figure 6). Originally, such 2 1/2-dimensional shapes used to be created in greater numbers using dies or specialized mouthpieces for extrusion. As in replacement-situations the required number of pieces is often too low to justify the creation of such formwork, AM appears as a suitable manufacturing method. Harmonizing surfaces may take place as discussed before in a post-processing step.

However, with regard to more complex geometries, the AM of Ceramics could unfold its full potential. In an attempt to recreate the articulate surface of a cornice composed from glazed ceramics, 3D Scanning was used to capture its geometry (Figure 7). Contrary to the paradigm that printing may take place with the largest nozzle possible, in this case mapping the detailed surface will require a high resolution and result in long processing times. While overhanging and bridging areas will not require support-structures, another challenge is to be seen in the surface-treatment. Though generally proved as feasible in other projects [21–23] little to knowledge is publicly available on glazing AM ceramics. as Being a project still in progress, yet soon to be finished, results on this are expected to be published in the near future.

Evaluating this methodology in terms of functionalization turns out to be more difficult than in the two aforementioned projects. Not only the geometric complexity differs from the individual components to be recreated, but also

Figure 4: Three different Types of additively manufactured Nesting Bricks in a Demonstrator.

Figure 5: Directly printed and optimized Nesting Brick in comparison.

Figure 6: Profiled Bricks for cornices, lintels or pilasters.

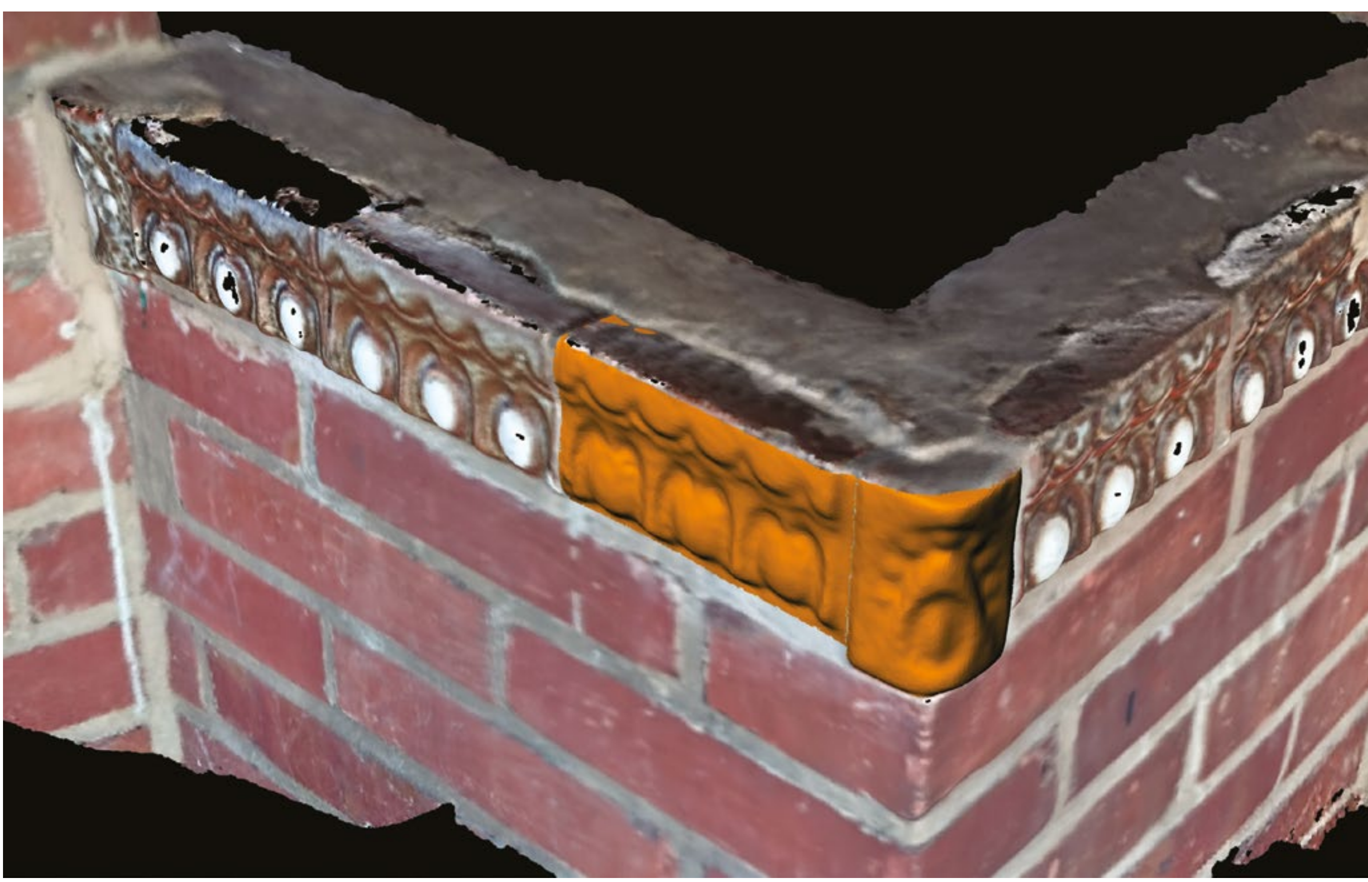

Figure 7: 3D Scan showing damaged historic ornaments from glazed ceramics. Replacements marked orange.

the required actions to produce and post-process them. With such components already being used in the complementary manner advised for AM ceramic components, this criteria may be seen as fulfilled. As the high relevance of preserving, maintaining and restoring historic buildings may be assumed as common sense, the author prefers to refrain from a discussion on the economic point of view.

CONCLUSION

Based on the three examples mentioned, it is apparent that the use of functionalized AM ceramics in architecture is generally well feasible. Yet, only low-tech approaches have been undertaken, which is due to the rather low resolution, as well as the relatively high tolerances inherent to the process of Robocasting.

Depending on the desired outcome, several strategies to achieve greater geometric freedom or harmonize surface-qualities are available. Together with optimizations regarding print-parameters, as i.e. the resolution, or a geometry's orientation during fabrication, a process of "design for additive manufacturing" is advised.

From an economic view on the topic, the use of AM ceramic components is recommended to be carried out in a complementary manner, combining them with mainly conventionally produced pieces.

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INTEGRATING COMPUTATIONAL DESIGN AND ADDITIVE MANUFACTURING IN CERAMIC-BASED MODULAR SYSTEMS

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Paulo J. S. Cruz

The integration of Additive Manufacturing (AM) in modular architectural systems combines the benefits of AM with the principles of circular tectonics. Following previous research here is presented the development of a modular architectural system composed of 3D-printed ceramic components, leveraging digital design tools, computational optimization, and hybrid material integration to enhance structural performance and functionality. The research explores the potential of ceramic materials in AM for architectural applications, emphasizing their compressive strength while addressing inherent brittleness through hybridization with complementary materials.

The study introduces a modular system designed using topological optimization principles to ensure efficient material distribution, integrating ceramics with strategic reinforcements to enhance mechanical properties. The fabrication process employs Paste Extrusion Modelling (PEM) to produce discrete ceramic components, which are then assembled into a structurally coherent system. Additionally, the system adheres to Design for Assembly and Disassembly (DFAD)principles, ensuring ease of repair, reconfiguration, and material reuse. By advancing the knowledge of AM in architecture, this research contributes to the sustainable evolution of ceramic-based structural systems, demonstrating their viability in contemporary construction practices.

INTRODUCTION

Additive Manufacturing (AM) has emerged as a disruptive technology in architecture and construction, offering unprecedented geometric freedom, material efficiency, and customization possibilities. The advent of digital fabrication has enabled the transition from traditional construction methods to highly optimized, computationally driven processes. Among these, AM has gained significant attention for its ability to produce intricate architectural components with minimized material waste and enhanced performance [1, 2].

Within the realm of AM, ceramic materials represent a compelling frontier due to their exceptional compressive strength, durability, and thermal properties. Historically widely used in masonry construction, ceramics have seen a resurgence with digital fabrication, allowing for the creation of complex forms that were previously unattainable through conventional means [3]. However, despite these advantages, ceramics pose inherent challenges, particularly in tensile resistance and brittleness [4]. These limitations have prompted research into hybrid material integration, combining ceramic components with components made of materials such as polymers, wood, metals, and composites to enhance mechanical behaviour [5, 6].

Another critical aspect of AM in architecture is the shift toward modular and prefabricated systems [7]. Unlike monolithic 3D-printed structures, modular fabrication enables the production of discrete, transportable components that can be assembled on-site. This approach aligns with the broader architectural trend of Design for Assembly and Disassembly (DFAD), which prioritizes adaptability, sustainability, and circular material use [8]. By implementing modular strategies, AM facilitates mass customization, allowing to produce bespoke elements while maintaining cost-effectiveness and ease of replacement. Computational design and topological optimization further expand the capabilities of AM by ensuring material placement aligns with structural demands. Through generative algorithms, designers can refine geometries to enhance load-bearing capacity while reducing material consumption. Such advancements have led to significant breakthroughs in lightweight and high-performance structures, contributing to the broader field of digital fabrication in architecture [9, 10].

Despite these advancements, challenges remain in scaling AM for widespread architectural application. Issues such as production scalability, material performance under varying environmental conditions, and integration with existing construction methods continue to be areas of active research [11]. However, as AM technologies advance, the potential for ceramic-based architectural systems to redefine contemporary construction remains substantial.

Building on these advancements in Additive Manufacturing and the integration of ceramics into modular architectural systems, the research presented here seeks to further explore material, structural, and fabrication parameters that define the feasibility and scalability of such approaches. To achieve these objectives, the study employs a methodology structured around three key interrelated elements: (1) analysing the characteristics of ceramic materials and evaluating potential supplementary substances to enhance performance, (2) utilizing topological optimization to strategically allocate material within structural components, and (3) refining component shapes and sizes to align with the capabilities of the production equipment. Through systematic experimentation and prototyping, this study aims to establish a comprehensive framework for the development and application of AM-enabled ceramic systems in contemporary architecture.

MATERIALS

The production of ceramic components for the constructive system relied on fine stoneware paste, chosen for its compatibility with production equipment and its remarkable compressive strength of up to 175 MPa when fired at 1260ºC. The material, free of chamotte and containing 35% water, was used uniformly across all prototypes to streamline the processes of design, production, and assembly. This decision allowed the focus to remain on refining system design and performance rather than managing multiple material compositions. The production method required the discretization of larger components into smaller, manageable pieces due to equipment volume constraints, which highlighted the critical role of effective connection and union between elements. Such connections were fundamental to ensure the structural system's functionality and reliability, distinguishing it as a viable alternative to traditional construction methods.

To address the inherent brittleness of ceramics and optimize its mechanical performance, especially under compression, complementary materials were tested to act as connecting elements between ceramic components. Compression tests were conducted on cylindrical ceramic specimens produced through Paste Extrusion Modelling (PEM), simulating real components. Materials tested included wood (oak), rubber (SBR), mortar (Sika glue), acrylic glue, and concrete (C-30 mixture). The specimens were developed with specific designs, such as three-wall cylindrical configurations, to evaluate the performance of each material in combination with ceramics. A total of 51 test specimens were created (Figure 1), covering various configurations: simple ceramic elements, stacked ceramic elements with and without separating materials, and concrete-filled ceramic components, alongside solid and hollowed concrete cylinders for comparison.

The results of the compression tests highlighted the potential of ceramics for load-bearing structures. Even without separating materials, stacked ceramic components displayed higher resistance values than equivalent concrete specimens. However, separating materials played a significant role in mitigating ceramics' brittleness. While rubber and acrylic glue caused instability and deformation leading to failure, mortar and wood proved more effective, enhancing the structural resistance and compensating for the ceramic fragile behaviour. These findings demonstrate the feasibility of combining ceramics with suitable complementary materials to create functional, durable structural systems with properties comparable to, or even exceeding, those of traditional concrete structures.

TOPOLOGICAL OPTIMIZATION

Although AM enables the creation of highly efficient components by depositing material only where necessary, its full potential is only realized when closely aligned with the design process. To fully leverage AM's advantages, a direct relationship between the production method and the design is essential. Topological optimization serves as a key tool in this context, balancing form, structure, and material. Using advanced computational tools like Rhinoceros® and

Figure 1: Complementary material specimens and concrete reference specimens for load bearing tests.

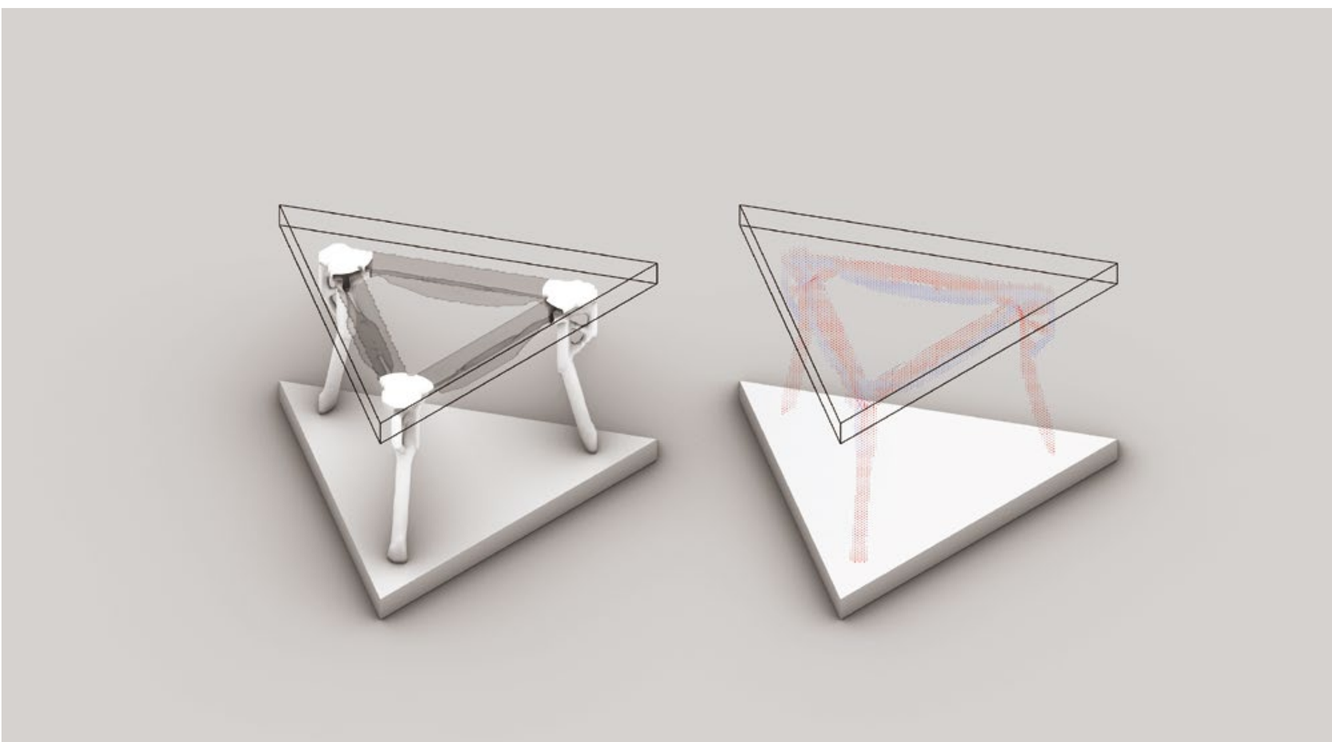

Figure 2: Topologic optimizations carried out during research.

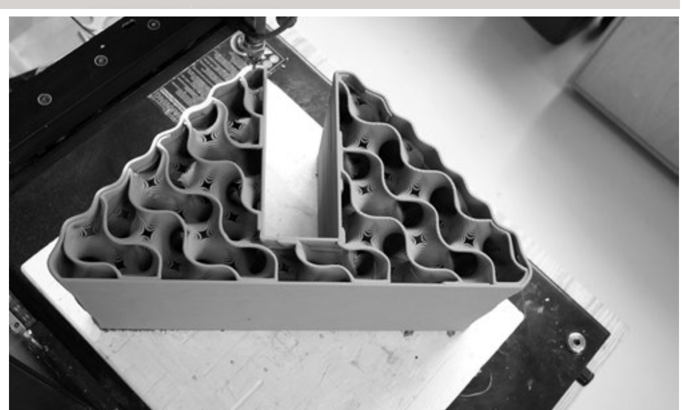

Figure 3: Printing process - Lutum 4.0 XL.

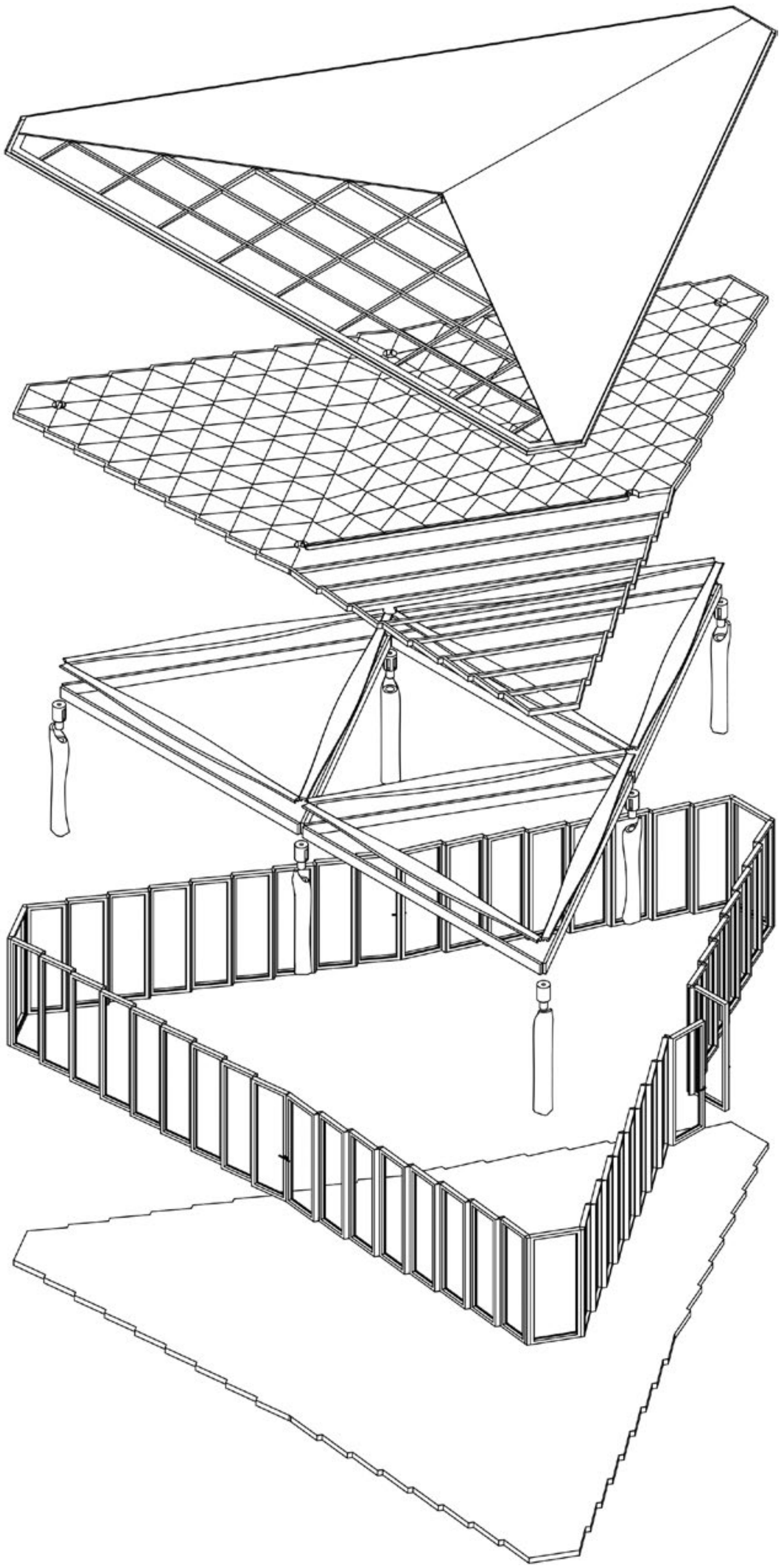

Figure 4: Exploded axonometric view of the hybrid architectural system.

Grasshopper with the tOpos plugin, this process optimizes material distribution for maximum performance and minimal waste. When combined with AM, topological optimization ensures precise material placement, fostering sustainable practices by reducing waste and promoting structurally sound, high-performance components.

In this study, a comprehensive topological analysis was conducted on standard structural elements, such as columns, beams, and slabs, to establish a well-informed and consolidated design framework (Figure 2). Fixed dimensions for these elements were maintained across tests to ensure consistent data comparison. The optimization results highlighted areas for material retention and removal, as well as the structural forces acting on each component. Based on this analysis, a digital model was developed that respects the distribution of masses and loads within the system. Compression zones were primarily addressed using ceramic materials, while traction forces were efficiently managed with wood and steel, resulting in a system that optimally balances material use and mechanical performance.

PRODUCTION EQUIPMENT AND PROCESSES

The production of ceramic components begins with creating the clay body, followed by shaping, drying, firing, and post-processing. Traditional methods like extrusion, moulding, or manual shaping require producing multiple parts to offset costs, but additive manufacturing introduces opportunities for precise, custom-designed ceramic components. This method employs a cartesian three-axis printer with a motor-controlled rotating spindle and a compressed air system for controlled extrusion. The primary control mechanism is a G-Code that governs every aspect of the printing process, from material flow to movement speeds. To achieve customization beyond standard slicing software capabilities, a Grasshopper computational model was developed, enabling precise control over dimensions and printing parameters. The system, though ideal for small-scale production and prototyping, highlights the need for more robust equipment for industrial applictions.

Post-printing processes are crucial due to the thin walls and substantial shrinkage of the ceramic material. Components undergo gradual and uniform drying to prevent breakage or distortion. Any imperfections are corrected, and contact surfaces are refined before firing. Components are carefully arranged in the kiln to optimize energy efficiency and ensure uniform heating. The firing process, essential for achieving the desired properties, involves significant transformations, including quartz inversion at 573°C and vitrification phases between 850°C and 1260°C, which result in a shrinkage around 25%. Adjustments to the firing curve were necessary to accommodate the dimensions and volume of the components, ensuring structural and geometric integrity after firing.

Finally, after firing, components are inspected for quality before assembly. The kiln's digital system allows precise adjustments to the firing process, promoting efficient energy use and minimizing thermal stresses. By integrating additive manufacturing techniques, customized control systems, and optimized firing processes, this methodology demonstrates the potential for ceramic components to expand the possibilities of masonry construction, blending innovation with traditional materials.

PROTOTYPE OF A MODULAR AM HYBRID ARCHITECTURAL SYSTEM

A possible modular architectural system composed of 3D-printed ceramic components was developed, leveraging digital design tools, computational optimization, and hybrid material integration to enhance structural performance and functionality (Figure 4). The prototyping phase aimed to explore the feasibility of these components, assess their mechanical behaviour, and identify potential challenges related to fabrication, assembly, and structural efficiency. By systematically investigating different structural elements—including columns, beams, slab blocks and its connections —this study establishes a framework for integrating AM in modular construction. Each of these components was designed and tested to evaluate its performance, adaptability, and potential for application.

A detailed development and evaluation of these structural components is presented. The columns serve as load-bearing elements, integrating hybrid materials to improve mechanical resistance and adaptability. The beams explore strategies for optimizing horizontal load distribution through ceramic-reinforced hybrid systems. The connections between structural elements focus on assembly techniques that enhance stability while maintaining modular flexibility. Lastly, the slabs investigate ceramic-based solutions for spanning horizontal surfaces, balancing strength, material efficiency, and lightweight design.

COLUMN

Following tests identifying wood as the most suitable material to complement ceramics, the focus shifted to designing structural elements for the main system, starting with columns. These columns were conceived not only for their structural role but also to provide thermal insulation, ventilation, infrastructure pathways, cladding, and enhanced

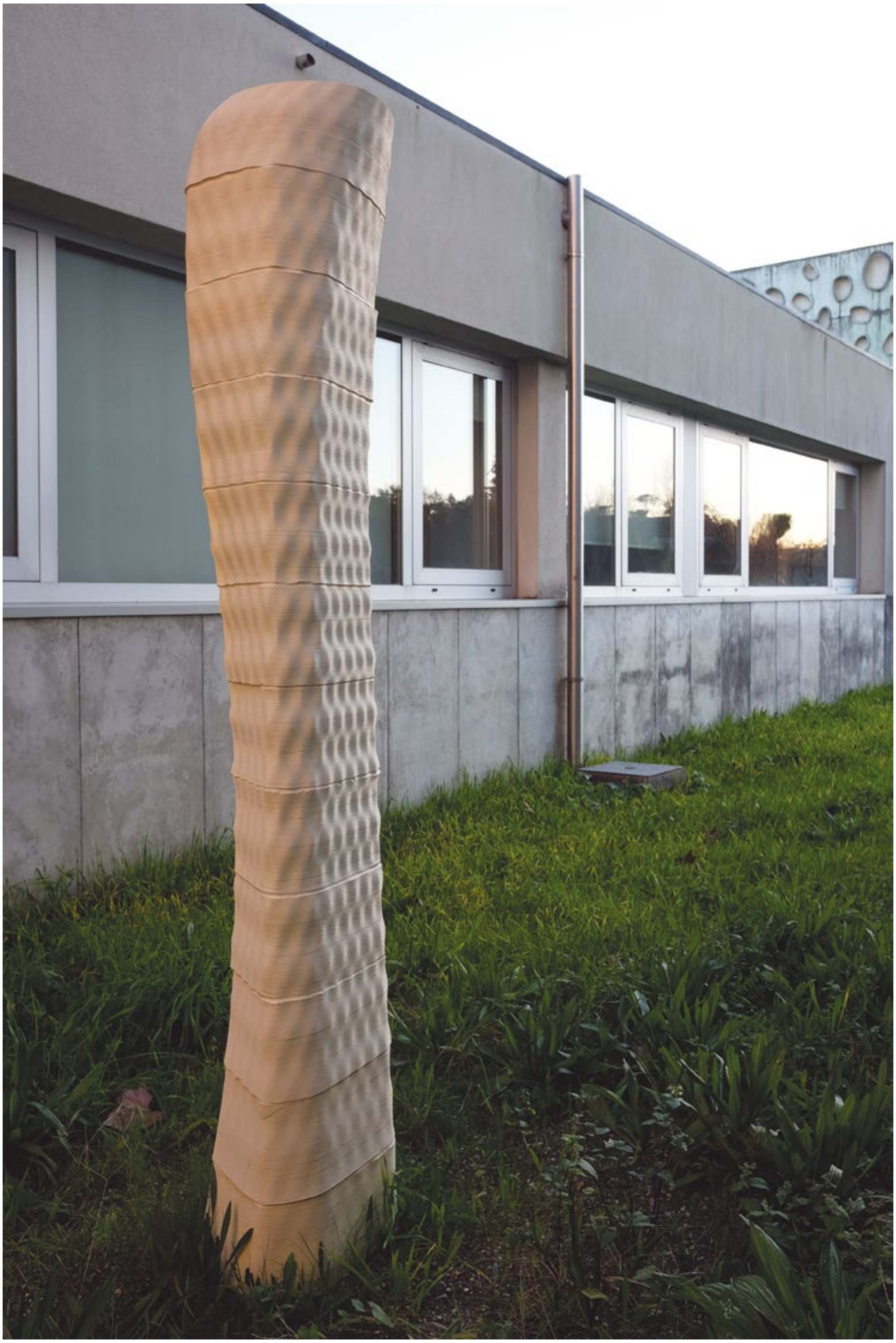

Figure 5: Hybrid column.

Figure 6: Hybrid beam.

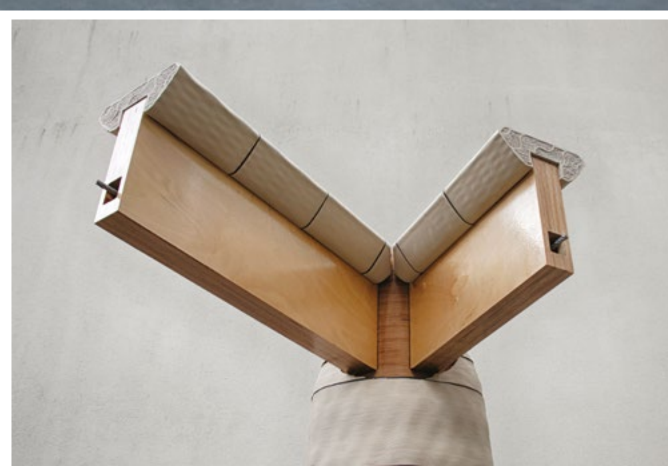

Figure 7: Connection between beams and columns.

fire resistance, emphasizing their potential to augment existing systems rather than replace them entirely. Initially designed as lost formwork for reinforced concrete, the columns evolved into an alternative system featuring ceramic staves with internal honeycomb structures, separated by MDF spacers to avoid contact. Topological optimization informed the column's shape and mass distribution, while a steel tensioning element was incorporated to compress the assembly into a monolithic unit and accommodate dynamic structural loads, ensuring strength and integration with other system components.

BEAM

Building upon the principles established with the column prototypes, the research transitioned to the development of beams as the next structural element. Unlike vertical elements, horizontal beams face distinct force distributions, with compression and tension acting in different areas, necessitating a hybrid approach. Ceramic components handle compression, steel resists tensile forces, and MDF boards facilitate load transfer and alignment. A 2,7-meter beam prototype constructed using hollow bricks, MDF, and galvanized steel rods, demonstrated excellent performance, withstanding significant loads without deformation.

To enhance the initial design, a novel model was developed using a wooden "core" to connect 30 ceramic pieces, reinforced with concrete to improve compressive strength and cohesion. This version optimized assembly and reduced the beam's weight by over 50% compared to reinforced concrete beams.

CONNECTIONS BETWEEN COLUMNS AND BEAMS

The connections between vertical and horizontal elements are crucial for the stability and load transfer in framed structures. In the developed constructive system, which uses discretized ceramic components and complementary materials, these connections are vital for solidifying the entire assembly, especially considering the system's non-monolithic nature and the potential for disassembly. Various connection concepts were developed, inspired by traditional construction methods, and categorized into four structural schemes with different blocking types. Ultimately, a functional connection was prototyped using wooden components for flexibility and ductility. These components, consisting of overlapping cylinders with specific cavities and a central hole for steel cables, connect columns and beams, reinforcing structural integrity and counteracting lateral movements. The steel cables passing through the components enhance the stability of both the beams and columns, effectively unifying them into a single structural unit.

SLABS

Slabs, as horizontal, planar elements that make up the floors and roofs of buildings, are essential components of a typical building system. In conventional construction methods, ceramic materials are often incorporated—either entirely or partially—into the creation of these fundamental structural elements. Prior to finalizing a system for the construction of slabs, a series of component geometries and operational approaches was considered for preliminary analysis. This process follows the same methodology used for the earlier architectural elements, with the aim of evaluating the potential of each typology to determine the best possible approach for the final system's design phase. The objective was to identify the most effective solution and any challenges that might arise during the implementation, laying the foundation for further refinement.

To proceed with the exploration of potential solutions, four distinct component types were conceived, each varying in mass distribution and structural schemes. These designs were influenced by traditional ceramic vaults and their operational principles, necessitating lateral beam supports for reinforcement and stability. The support elements designed for these components, used to assess the maximum capacity of each geometry, were made entirely of wood, closely following the section design of traditional prestressed beams. Each type of component included two lateral supports: one at the top and one at the bottom. The mechanical tests conducted on these components revealed significant differences in their capacity to withstand stress. Types A and B demonstrated positive results, with type A achieving an average capacity of 10 kN and type B reaching 7 kN, despite having thin 1.5 mm thick walls. However, the performance of types C and D was far beyond initial expectations, with their mechanical resistance proving much higher than the previous types. Even when subjected to the maximum allowable capacity of 45 kN, it was not possible to push these components to their breaking point in the initial phase of testing. All specimens of types C and D were subjected to tests with a wooden base and applied force up to the 45 kN.

Given that the ultimate goal of these tests was to determine how each component responds to compressive forces, the investigation proceeded by pushing the specimens to failure, subjecting them to additional tests under more challenging conditions. For this second round of tests, the wooden elements, which had previously been used to simulate beam supports and absorb surface tensions, were replaced with steel components to create more unfavourable conditions for the ceramic material, thereby reducing its mechanical strength. The results of these tests confirmed that type D exhibited the highest stability and resistance among all the components analysed, establishing it as the most reliable option.

After the testing phase was completed, the next step was to produce a section of the slab, which would eventually be assembled with the other prototypes. The design of this slab adheres to the same principles of mass distribution as the topological optimization models used for other components of the constructive system. However, there is still room for further rationalization and simplification of the geometries to ensure better compatibility with the production equipment available. The slab system is based on the same concept applied to beams, using longitudinal wooden elements that rest directly on the main beams. These wooden elements serve as the foundation for placing the ceramic vaults, replicating the operational structure of conventional lightweight slabs. To enhance the mechanical capacity of the system, post-tensioning elements may be incorporated into the wooden beams without significantly increasing the dimensions of the slab components. Once the joists and vaults are assembled, a cork plate, approximately 5 mm thick, is placed over the vaults to further consolidate the structure. Wooden boards are then attached to the beams using screws, and the final flooring is installed on top of these wooden boards, completing the assembly of the slab. This design allows for both the structural integrity and flexibility needed for the final system, demonstrating a promising integration of traditional materials and modern construction techniques.

RESULTS AND DISCUSSION

The system developed in this research, along with the principles guiding its design and the practical results achieved during the prototyping of various models, reinforces the belief in the viability of manufacturing medium-sized ceramic architectural components using PEM. These components can be effectively integrated into real-world contexts, transforming the built environment into a more cohesive and environmentally conscious space. The proposed system represents a major step forward in sustainable construction methodologies, offering the flexibility to customize each element for specific performance, form, or function while ensuring seamless integration within a unified framework.

By strategically allocating materials based on a structural arrangement derived from topological optimization, the system ensures optimal material performance under various forces. Additionally, design principles for assembly and disassembly allow for the creation of a fully reversible system that can be easily repaired or modified—damaged components can be replaced without significant limitations. This approach optimizes material usage throughout the entire process, from design to production, contributing to the development of a more sustainable built environment. The compression tests conducted validate the material's considerable potential for use in load-bearing structures, demonstrating that ceramics offer substantial advantages over traditional concrete, which is commonly used for such applications.

While the findings are promising, it is essential to recognize the challenges inherent in this production process, especially regarding the material properties and their varying responses at different stages of production. The system presented was initially developed within a controlled laboratory and experimental context, and transitioning to practical construction applications would require necessary adjustments. The production equipment used is designed for small to medium-scale components and limited production volumes. Furthermore, controlling the different phases of ceramic material, particularly during drying and firing, presents challenges. To improve the system's scalability, consideration should be given to materials with lower shrinkage and reduced deformation during these phases, ensuring the structural integrity of larger components while facilitating their practical application. For this investigation, fine stoneware without chamotte was selected for its adaptability to the extrusion system, but for larger-scale components, a different material might be more appropriate to avoid potential issues during production.

ACKNOWLEDGEMENTS

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Figure 8: Types of slabs components.

Figure 9: Hybrid slab.

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THE DUALITY OF CLAY AND CONCRETE

Cristina Nan

This paper discusses the duality between clay and concrete within the framework of additive manufacturing. Particularly in the case of 3D concrete printing, the monolithic approach of continuous printing of large-format architectural elements is being prioritised. Contrary to this path, this paper examines modularity and configurability for both 3D clay and concrete printing. This represents a means of extending the life-cycle of components and architectures by designing for reuse and adaptability. This is showcased through a fundamental architectural element, the column. The tectonic expressivness of the developed structures is being discussed through the lense of computational ornamentality and digital craftmanship.

INTRODUCTION

The complex implications of climate change, the climate crisis, material scarcity and extractive industries for our societies are widely discussed and known. The role the construction industry plays in this environmental equation, particularly the use of steel and concrete, are extensively cited at the beginning of numerous scientific papers. The 2024 report by the UN titled "Building Materials and the Climate: Constructing a New Future" states the following: "The built environment sector is by far the largest emitter of greenhouse gases, responsible for at least 37 per cent of the global emissions"[1]. It highlights the importance of decarbonizing the construction sector, particularly through the reduction of embodied carbon emissions. Currently the use of concrete for structural and infrastructural purposes cannot be fully avoided. Additionally, the construction sector is notorious for its slowness in implementing large-scale industrial changes and novelties. Therefore, it is quite likely that concrete will remain in the foreseeable future a commonly employed material. Yet, by complying with the paradigms of circularity by extending the life cycle and reuse of components, its environmental impact can be diminished. This can be addressed by further advancing modularity and reconfigurability in the design process. As discussed in more detail in this chapter, 3D concrete printing (3DCP) is often used following an approach of monolithic production, which hinders reconfigurability and repurposing of the elements themselves. A changed paradigm of modularity for 3DCP can alter this.

While concrete is employed for large-format architectural components relating to structure, clay is a building material that is rather used for the production of smaller scale elements. Historically, clay is a material that has been broadly employed in architecture under the form of bricks and as tiling be it for facades, interiors or as a cladding system for roofs. In building interiors, clay or ceramic materials (the fired version of clay) is encountered in wet zones such as bathrooms or kitchens, as tiling for walls, ceiling or floors. Within contemporary research in architecture, additive manufacturing with clay still covers similar application areas. The PolyBrick 2.0 [2], the Ceramic Information Pavilion composed of 882 custom bricks [3]manufacturing and assembly. In the modern era, this has been perceived as a significant drawback, and as such has resulted in brick construction being partially superseded by more rapid methods of fabrication, despite its inherent robustness and longevity. This paper describes the second stage of an ongoing research project which attempts to revitalize the material system of the brick special through the development of an intelligent 3d printing method that works in conjunction with a layman assembly procedure for a new class of self-supporting nonstandard brick structures. In this project, an indexed and geometrically informed jointing system, together with a parametric and digital workflow, enables rapid assembly on site without a requirement for complex site setup or skilled labor.","container-title":"Intelligent & Informed","event-place":"Wellington, New Zeeland","event-title":"24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA and an interlocking 3D clay printed masonry screen wall developed at the University of Waterloo [4], all showcase computational bricks with varying degrees of ornamental expressivity originating from a computational design strategy. Research projects on ceramic additive manufacturing used for facades are Ceramic Morphologies developed at Harvard University [5] or Clay Non-Wovens developed at Cornell University [6]. Built examples include notably the Seed Stitch wall by Emerging Objects [7] or the finalized 3D clay printed façade for a commercial building in Amsterdam by Studio RAP.

Despite this list of reference projects, clay's potential for architectural applications through the use of additive manufacturing is still underexplored, comparatively to 3D concrete printing. This is the case particularly concerning large format elements such as columns or wall systems. This is of course due to its reduced strength in comparison to concrete and its limited use for structural purposes. Despite these material constraints, the exclusion of clay for such applications may hinder its architectural and tectonic potential. Other than concrete, clay is "a material with interesting environmental advantages: high adaptability to different climates, a low carbon footprint, high resource availability and renewability" [8].

THE DUALITY OF CONCRETE AND CLAY

In architecture, the interchangeability of materials in terms of design is limited and considered problematic. Each material choice implies a particular system thinking in accordance with material behaviour, structural systems and its constructive nature. Material changes require also a rethinking of the fabrication strategy. Replacing one material for another often implies significant changes of the entire system logic, from computational design to fabrication logic.

Liquid deposition modeling (LDM) is an extrusion--based technique using a paste which can be based on different material material mixes. These mixes showcase varying viscosities correlated with adapted extrusion rates and speeds. Therefor LDM allows for a slightly increased flexibility when it comes to the interchangeability of clay for concrete, yet not without its own challenges.

Clay and concrete posess different material properties which come along with their specific set of parameters for robotic fabrication. Due to its structural performance, clay is limited regarding its scalability for large-format architectural elements. Clay has significantly higher shrinkage rates than concrete, and is prone to warping particularly during the firing steps. 3D printed clay may shrink in a non-uniform manner depending on infill types and the geometry of the design. Layer adhesion, buildability during printing and curing times differ too. This translation process and the resulting design iterations as well as changed material expressions will be discussed within the context of selected case studies.

CCP – COMPUTATIONAL CLAY AND CONCRETE PROTO-STRUCTURES

The series Computational Clay & Concrete Protostructures (CCP) was developed in a collaboration between Assistant Professor Cristina Nan and architect Mattia Zucco at the Eindhoven University of Technology. It follows a dual line, being both an ongoing research-lead teaching endeavor as well as a self-standing research line. CCP, as a research-led teaching series, builds up over the past 4 years on consecutive design themes explored in postgraduate seminars and design studios. The aim is to investigate advanced computational workflows and robotics fabrication with clay and concrete not as experimental ventures but as 'normalized' design-to-production tools within the framework of the architectural discipline. Curating process, understood as the loop between design, material and production, stands at the center of this. The CCP-Series focuses on archetypical elements such as the column, the vault, the dome and the skin. Through material experimentation we explore the boundaries of how the ornament and the ornamental may be redefined within the context of computational architecture. Within this writing the outputs relating to the column as an experimentational field will be showcased and explained.

THE COLUMN – A CAROUSEL OF THE MONOLITH AND THE ASSEMBLED

Additive manufacturing has advanced rapidly in the past years in the architecture and construction sector. One of the most common architectural elements through which the potential of 3D concrete printing has been explored is the column. This is not surprising, as the column is integral to most architectural designs and lends itself particularly well for continuous, layered printing due to its verticality. Through the use of 3D concrete printing a wide palette of geometric exploration is opened up for designers, which would be difficult to achieve through traditional fabrication methods. In the project Concrete Choreography [9], layered extrusion printing with concrete is used for the column series. Alternatively, the project Eggshell employs FDM 3D printing with PET-G for the external formwork [10] with subsequent concrete casting. For the Marinaressa CoralTree, a fully recyclable 3D printed sand formwork is used for the casting process [11]. These projects depict monolithic column outputs. Although characterized by a time and labor-efficient production line, difficulties emerge in the next logistical phase. Due to offsite production, the handling, transport and on-site installation of the concrete elements is more complex due to weight and size of the elements. A modular setup allows for an easier fixing or replacement of damaged parts. Reuse and adaptation of the segments remains always a possibility, other than in monolithic fabrication approaches [12].

As the above listed references, the wide majority of 3D concrete printed columns are based on a monolithic approach, meaning that the column is printed as one continuous element. This commonality is rarely questioned and contextualized within architectural history. More specifically, in computational architectural discourse the tectonic evolution of the monolithic is rarely invoked or to begin with understood in its full complexity. A closer study of this topic may offer relevant insights into the positioning of large format additive manufacturing within the disciplinary development of architecture and tectonism.

The history of the monolithic, of the evolution of architectural monoliths (be it fundamental architectural components such as the column or entire architectures) is a complex one and differs depending on specific cultures and across continents. This here built up narrative is by no means exhaustive and is mainly anchored around the extended European ancient architectural history. It serves the purpose of positioning this research within a broader historic timeline.

The term monolith or monolithic is used within this text to describe large-format architectural elements or even architectures (buildings) formed of a single, continuous large block of material. In ancient architecture this material typically would have been stone. The monolithic approach of making or fabrication is atypical in architecture and construction, both in the past and present. Often it presents itself in conjunction with the fabrication logic of excavation or subtraction and not addition as practiced through additive manufacturing. Rock-cut architecture exemplifies best this approach to construction. Vernacular examples of monolithic architecture through subtraction is for instance the Kailash Temple in India. Examples of large-format monolithic architectural elements are the columns of ancient Egyptian temples, the Greek temple of Apollo in Sicily, the portico columns of the Roman Pantheon or the monolithic dome of the mausoleum of Theodoric in Ravenna. Monolithic architectural elements are rare in modern architecture, as it rather follows an approach of integrated tectonic systems. Both in ancient and modern times, the monolithic approach poses significant challenges during its making so excavation, handling and transport. Subsequent changes are hard to implement. Particularly in the case of off-site fabrication, the logistics of positioning are prone to material failure or damage of the element. Due to this, ancient architecture often treats the column as an assembly of parts, be it drums or bricks. Selected examples of vertically stacked drums forming columns are Trajan's Column in Rome, the Delphi Columns, the Acropolis Hill, and the late Archaic Temple of Poseidon at Sounion. Additionally, columns made as assemblies of stacked drums showcase a higher earthquake resistance than monolithic ones. Apart from drums and monoliths, columns were naturally also constructed from bricks and clad with plaster. The Forum Romanum or columns from Pompeii exemplify this technique.

NORMALISING & CONTEXTUALISING AM

One key feature of the CCP-series is the attempt to contextualize computational design and robotic fabrication. Given their nature, research and research-led teaching activities on these topics often focus on the technical and material dimension. Consequently, resulting designs and prototypes are context-free and not site specific. They are treated as standalone objects, demonstrators and exhibition pieces. If additive manufacturing is to be treated as a combined material-fabrication system ready to replace already *today* environmentally problematic systems such as precast concrete or extruded steel, then it needs to be normalized within design studios as a conventional system for design for today's generations of architects. This requires an understanding of the intricate correlations between geometry, material and tool (the robotic arm). Additionally, designing with site-specificity in mind, as within any other architectural design studio, should be a baseline requirement within the academic curriculum for design studios on robotic fabrication. Not doing so, maybe a reason why the technical excellence is not necessarily matched by design originality. Particular images of computationally generated geometries from leading institutes dominate the imagination and awareness of today's designers and students, leading to repetitive, self-referential design proposals with additive manufacturing. It is important to break free from those predefined formal expressions.

Often the physical artefacts resulting from computational research and experimental robotic fabrication in academia are being designed and developed without a specific context or site. This may be valid from a point of view of technological innovation. As a consequence, such prototypes are removed from context, rarely presented as part of a larger architectural framework or composition, being often exhibited as standalone design objects and not architectural elements within a defined context. Digital materiality and complex computational geometries or surface expressions are derived from a self-contained logic, that is motivated through a self-imposed computational challenge rather than contextual considerations. Within the scope of architectural research, we view this approach as problematic. The aim is to inform complex computational geometric approaches and surface expressions via a given context, embedding specific cultural notions in the digital and material workflows.

THE BIO-INTEGRATED COLUMN

The Baths of Caracalla are located in the Southern part of Rome and were one of the biggest ancient bathing complexes. The architectural scheme of the baths is based on a repetition of columns and colonnades, most of which did not survive the centuries. Some of these were monolithic granite columns, others made up of drum segments [13]. Part of the maintenance strategy as the ruins is to keep flora and fauna under control within the historic site. The bio-integrated column was developed to accommodate in a responsible manner plant growth and to offer spaces for inhabitation for birds and insects. A site-specific research resulted in a defined group of plants and animals to inhabit the cladding system (fig. 1). In the development of the column system aspects such tectonic expressiveness through ornamental expression played an important role, beyond the mere functionality of the column itself.

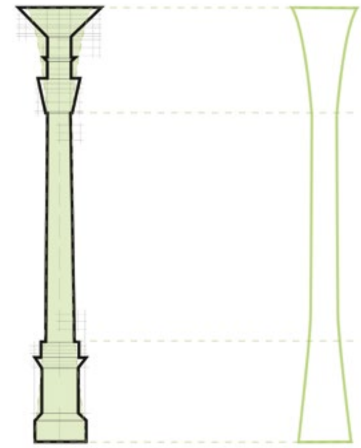
The bio-integrated column originates in the idea of developing a ceramic cladding system mounted onto a structural steel pole in which computationally derived ornamentality of the skin is used not only as an expressive means but as a substrate for nature-inclusivity and biodiversity. Subsequently, the functional and ornamental logic of the 3D clay printed cladding system was adapted and translated to a column system, fabricated through additive manufacturing with concrete. The translation process and the material iterations will be described in the following subchapters.

CERAMIC CLADDING SYSTEM

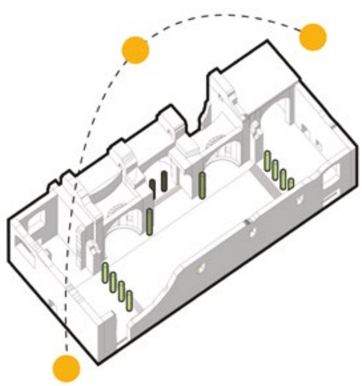
The ceramic cladding system integrates planters for short-rooted vegetation paired with two types of surface articulation for insects, birds and small-scale animals to grasp onto. The size of the pockets on the columns is determined by the spatial needs of native plants observed growing on ruins in Rome [14]. The plants were further grouped and distributed on the site based on their sunlight and spatial requirements, such as root depth and height. For example, plants that grow vertically and require substantial space were placed in the lower pockets, where they had room above them. Those with high sunlight needs were positioned on the southern, sunnier sides of the columns. In order to prevent the accumulation of water within the pockets leading to the rotting of the roots, the ceramic pockets contain drainage holes. These are incorporated directly within the g-code or printing path. The ornamental pattern on the planters resembling pulled strings provides a rough surface area for birds, small reptiles or mammals to hold on to, facilitating a vertical movement along the column. Additionally, this three-dimensional pattern is meant to accommodate moss growth and the inhabitation by insects.

Modularity and reconfigurability were relevant design parameters for the cladding system in order to facilitate adaptability to different sites and replaceability of potentially damaged components. As depicted in figures 2 to 4, different subdivision strategies for the ceramic skin were tested based on 3 and 4 segments mounted around a vertical steel pole to then individual ceramic drums to be vertically stacked along the pole. The step from a 3 or 4-part interlocking system, although successful, to a full drum-element is motivated by the intent to further simplify the assembly sequence. The interlocking cladding system

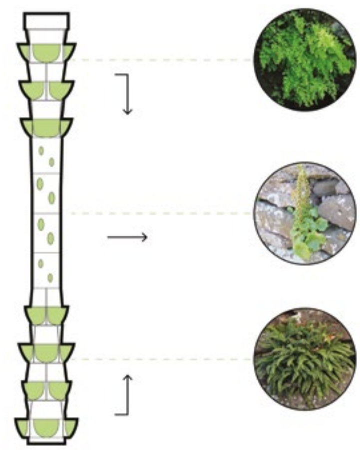
1
CONNECTING TO THE RUINS
Design incorporating greenery as a reflection to the site's genius loci - growth to new life throught the ruins.



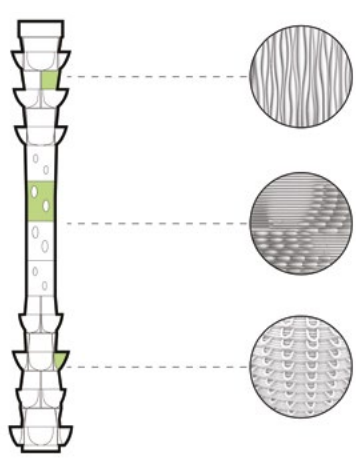
2
PROPORTION STUDY
Column general form derived from taking reference of the ratio and proportions of Corinthian columns that sre mostly found on site.



3
PLANT TYPES DISTRIBUTION
Plants types (climbing, horizontally, growing, hanging) are distributed reflecting on the general hourglass form of column.



4.
SUN HOUR ANALYSIS
Total hour of sun exposure on column positions determine types of plants distribution (sunny / shady / versatile).



5.
POROSITY & TEXTURE
Textures are implemented on the wall and pockets of columns in gradual transition to provide growth surface for plants.

Figure 1: Site integration and relevant design parameters for the 3DCP column within the Baths of Caracalla (Image: TU/e, Nikolett Ásványi, Loy Xin Yi, Maria Verhulst Babb, Maia Kilch)

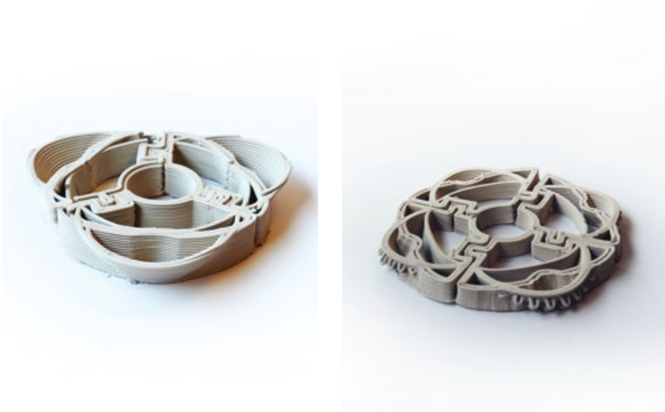


Figure 2: Three and four-part cladding prototypes, 3D clay printed (Photographer: Dena Khaksar).

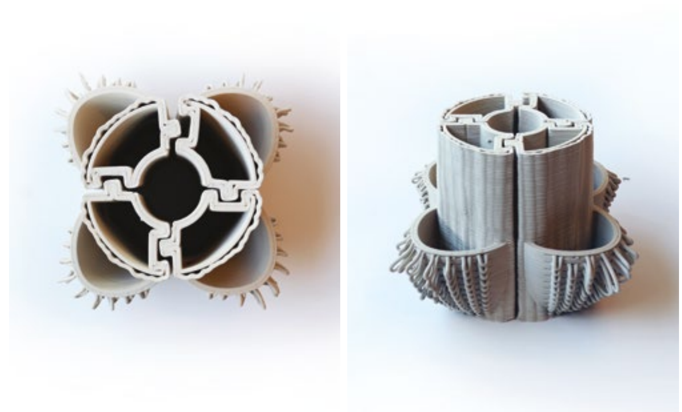


Figure 3: Four-part cladding prototypes, 3D clay printed, (Photographer: Dena Khaksar).

Figure 4: Singular cladding component showcasing ornamental computational patterns, 3D clay printed (Photographer: Dena Khaksar).

Figure 5: circular 3D clay printed drum segment (Photographer: Dena Khaksar).

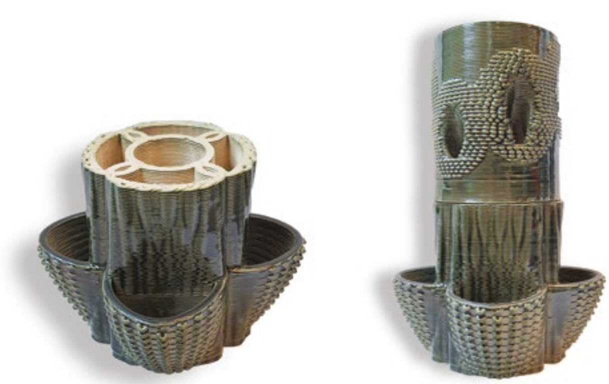


Figure 6: glazed and partially stacked 3D clay printed drum segments (Photographer: Dena Khaksar).

requires an additional fastening system between the cladding and the vertical steel profile. By opting for a stacking system this becomes obsolete.

SET-UP FOR CLAY PRINTING

All material experiments were undertaken with a WASP 40100 LDM with a 4 mm diameter nozzle, a layer height of 2mm and connected to an external continuous feeding system which guarantees a consistent material flow as it replaces the need for a tank with a compressor. For all prototypes a double layer wall thickness was employed to increase the stability of the elements. Commercially available clay with 25% chamotte as a wet paste was used, without additives. To improve viscosity for 3D printing, only an added 2.8% water was mixed into the clay with an industrial mixer for homogenization. The experiments were conducted at room temperature within the digital fabrication laboratory. Printing speed and flow vary during the fabrication process. These variations are related to the component height and specific computational pattern to be printed. Depending on the geometric articulation, 3D clay printing poses challenges related to non-uniform shrinkage and warping, both during the drying and firing stages. Based on prior experiments with ceramic additive manufacturing, closed volumetric geometries such as the drum-like components present little to no warping during drying and firing (fig.5). Segmented geometries or interlocking systems are more prone to warping and non-uniform shrinkage, thus affecting the functionality of interlocking joints. The simultaneous printing of the segments in their assembled position will significantly minimize or fully prevent warping during the subsequent drying process [15]this paper presents a hybrid method for designing with 3D printed clay that combines craft-based and theoretical ways of thinking with simple computational procedures. The method is described through the design and fabrication of an experimental ceramic cladding system for structural steel that allows the architect to consider how to dress a column with clay.","container-title":"Structures & Architecture: A Viable Urban Perspective? : Proceedings of the Fifth International Conference on Structures and Architecture (ICSA 2022, [16]the column. The Computational Clay Column is treated as double system made out of core and skin, both fabricated with 3D clay printing. The underlying principle is the spatial self-interlocking of the two subsystems, core and skin, thus eliminating the need for a substructure or fastening. A particular emphasis is placed on the infill beyond its stabilizing function. Expressive and ornamental value is not only assigned to the skin but also translated to the infill. Based on a conceptual strategy of unwinding, the infill is punctually exposed, showcasing it to the viewer and amplifying the ornamental aesthetic and digital materiality of the computational design strategy and robotic fabrication logic. By exposing the core with its ceramic self-interlocking system, the tectonic expressiveness of the column as an architectural archetype is amplified. The research discusses the computational workflows, material experimentation, the interlocking and assembly logic, fabrication strategy as well as the concepts of digital craft and digital materiality. The applied methodology is based on research-through-design. No prioritization is given to form over material and process of production. The knowledge derived from analog and robotic material experimentation as well as clay's specific material behavior relating to drying, shrinkage and warping are used to inform the design, production sequence and fabrication logic.","DOI":"10.52842/conf.ecaade.2024.1.055","event-place":"Nicosia","event-title":"eCAADe 2024: Data-Driven Intelligence","language":"en","page":"55-64","publisher-place":"Nicosia","source":"DOI.org (Crossref. The same strategy is also applied during the two firing stages: the components are placed in their interlocked position. The first firing is a bisque firing at 800 degrees, followed by a second round at 1200 degrees for the glazing (fig.6). Through the firing the clay body is transformed into the material group referred to as ceramics. Due to this approach, both the segmented cladding system as well as the drum-like segments did not present any warping during the drying or firing process allowing for an unproblematic assembly.

The resulting ceramic cladding system is lightweight, easy to assemble and disassemble. Due to the material behavior of clay it presents structural limitations, posing difficulties in scaling up the system. The depicted prototypes fit within a radius of 25cm and their structural performance depends on the inner steel pole. Scaling up the radius as well as the height of the clay drums brings along further production difficulties. Larger segments necessitate an increased drying time. The clay body needs to be fully dry before firing, otherwise cracking or even small explosions during firing within the kiln can happen due to remaining humidity within the clay. Due to the mass and density of the clay drums in their reduced scale of 25 cm, a drying time within the lab space of up to 4 days is required. In the absence of a drying chamber, this time would significantly increase, leading to a production process that would be inefficient from the perspective of time-efficiency. Further limitations are imposed through the size of commercially available kilns. In order to be able to transgress from a cladding system for columns to an actual column, another material choice was needed. This led to the transition from additive ceramic manufacturing to 3D concrete printing.

TRANSLATION FROM CLAY TO CONCRETE

The logic of the ceramic cladding system had to be altered in the translation process from clay to concrete, a process not without its own challenges. The column height was adapted from 200cm to 310cm, with a constant drum height of 27cm and alternating diameters ranging from 43cm to 39cm (fig. 7). The large format printing requires a rethinking of the slicing strategy as showcased in figure 8. All prototyping is based on the use of internally developed slicers, no commercial slicing software is being used. Due to a change of the layer height and width when working with concrete, the resolution of the ornamental patterns had to be adapted. The layer height was significantly changed, from 2mm for clay printing to 7mm, as well as the layer width from 3.5mm to 21mm. The modification of the printing parameters results in an altered architectural and tectonic expression which could be characterized as 'monumental' compared to the materiality of clay.

This alteration led to a decreased resolution of the base pattern, while at the same time offering an increased stability of the pulled string pattern. The pulled string pattern on the planters is further accentuated by the means of intended over-extrusion. In prior clay experiments, even in its fired form, the pulled string pattern could be damaged with relative ease due to the thin layer width and its relatively large overhang. Top and bottom parts of the columns are equipped with in-built planters, whereas the drums that make up the shaft showcase dispersed deep recesses. These indentations are meant to offer a protected nesting ground for insects and small reptiles.

Although the concrete version of the computational column could have been printed as a monolith, the logic of modularity and reconfigurability was maintained. The resulting column design is based on 11 drum segments and 2 caps, one for the base and for the top. The top cap prevents rain water from accumulating within the interior of the column whereas the bottom one creates a shadow line between floor and column. In order to increase structural stability, pipe-like extrusions, "necks", were added to the top of each of the 3D concrete printed drums. Due to the increased size of the printed concrete layers, the seams that during printing when moving upwards from layer to layer can be visually very dominant. These have to be addressed as an integral part of the design and not just a byproduct of fabrication. For this purpose, the printing seams of the planter segments are rendered invisible through articulation of the geometry by being integrated within the folding edge of the planters.

ASSEMBLY

As mentioned beforehand, the column is made up as a modular interlocking system, designed for dry assembly, meaning without the use of mortar. The complexity of logistics of transportation and on-site handling are thus significantly reduced. The column drums alternate in their individual weight between 25 and 50kg. Up to a height of 150cm the different drums can be stacked manually. The presence of the vertical necks integrated on the column drums increases the stability of the column. After a height of 150cm the drums are stacked with the help of a forklift or a cherry picker (fig.9). Due to the modularity of the drums, these can be assembled in different sequences, allowing for reconfigurability. Relocation within a different context and its adaptation to it by for instance changing its height is made possible.

PIGMENTATION AND COLOR SCHEME

Clay requires a double firing for glazing and color, once at 800 degrees, bisque firing, without glazing, followed by a second firing stage with glazing at 1200 degrees. This double-process is energy intense and significantly increases the carbon footprint of ceramics.

Contrary to popular perception, ancient building sites often exhibited vibrant color combinations in the interiors and on the exterior facades. Leaning on this tradition, also in case of the 3D concrete printed column, a decision was made to integrate color to further articulate the ornamental expression of the skin (fig. 10 and 11). For 3D concrete printing, within the custom robotic setup of our industrial partner Vertico, a 3D concrete printing specialist, pigment is mixed directly with the concrete during the printing process. This allows for custom color gradients and pigmentation strategies. A graded green color scheme was chosen to allow the blending in of the column within the context of the Caracalla Baths. In figure 12 the spontaneous inhabitation by a snail of the on-site mounted column is documented.

CONCLUSIONS

Implementing concepts of modularity and reconfigurability to 3D concrete printing harbors an immense disciplinary potential for the understanding of tectonics through the lens of additive manufacturing. Implementing systematically these two approaches can extend the boundaries of architectural flexibility, scalability and reusability for large-format additive manufacturing. Replacing the monolithic mindset with the modular one in AM allows for on-demand replacement, repurposing of components as well as for scalability over

Figure 7: 3D concrete printed stackable column drums
(Photographer: Cristina Nan).

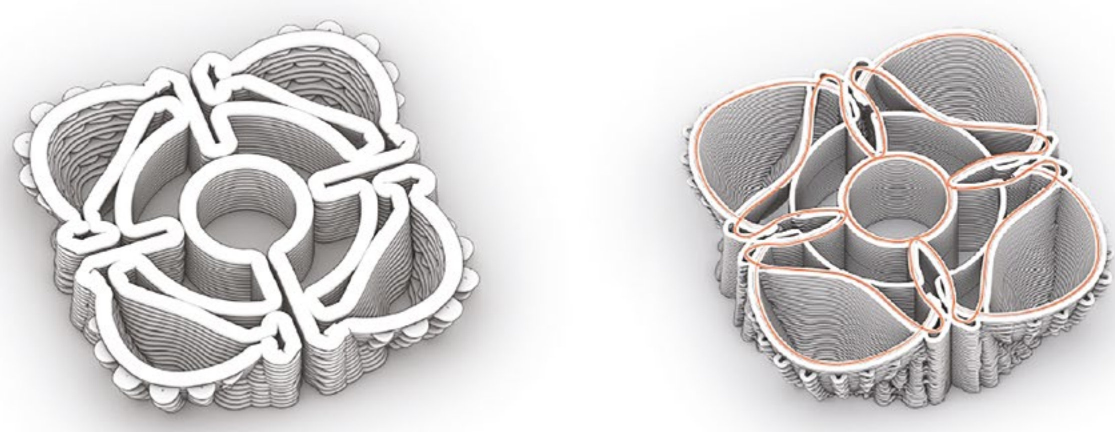


Figure 8: Column drum in concrete vs. clay .

Figure 9: Assembly sequence at Dutch Design Week 2024 (Photographer: Yorit Kluitman).

Figures 10-11: Assembled 3D concrete printed column showcased at Dutch Design Week 2024.

Figure 12: Close-up of snail randomly inhabiting the concrete surface, Dutch Design Week 2024(Photographer: Dena Khaksar).

time by adding new modules to prior fabricated structures to extend their functionality. The shift from monolithic printing which results in “static” structures to modular 3D concrete printed assemblies, can be interpreted as a shift towards adaptable, scalable and thus “dynamic” systems in 3DCP.

FUTURE STEPS

Engaging with the duality of clay and concrete continues as part of the CCP-series by further extending the modularity concept for columns. The column is not only viewed as an assembly of drums, but is being further applied by a subdivision into skin and core components. First experiments based on the interplay of clay and concrete have been already undertaken. This sub-line of investigation runs for now under the title “Unwinding the Column”. As shown in figure 13, skin and core of the 3D concrete printed column are visibly detached from one another. This logic of segmentation and conceptual delamination will be followed by separated functional integration within the skin and core such as ventilation, cooling or light installation.

If successfully executed, the balancing act between computational customization and the constraints of modularity can offer higher returns on efficiency, expanded life cycle and material use.

ACKNOWLEDGEMENTS

- The here described research-led teaching outputs were made possible through the “BOOST! - Teaching Innovation” funding scheme of the Eindhoven University of Technology. All showcased clay printed prototypes were produced at the 3D Clay Lab of the Eindhoven University of Technology. 3D concrete printed prototypes have been fabricated at the robotic facility of the 3D concrete printing specialist Vertigo.
- The concept of the bio-integrated column was developed as part of the CCP-studio series by the students: Nikolett Ásványi, Loy Xin Yi, Maria Verhulst Babb, and Maia Kilch. The computational design and optimization for robotic fabrication were addressed by Nikolett Ásványi, Mattia Zucco, and Cristina Nan.
- The “Unwinding the Column”-Prototype was developed as a collaboration between Cristina Nan and Mattia Zucco, relating to the ongoing CCP-series. Additional computational support was offered by Nikolett Ásványi. The column was executed in collaboration with Vertico (NL) and the specialist company Lanxess (DE) which provided the pigments and correlated expertise.

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Figure 13: "Unwinding the Column", 3D concrete printed column showcased at BE-AM 2024, Frankfurt (Photographer: Malcolm Unger).

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3DCP OF ARCHITECTURAL COMPONENTS WITH COMPLEX GEOMETRIES

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Aires Camões
Paulo J. S. Cruz
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Driven by the evolution of digital processes in architectural design, the integration of Additive Manufacturing technologies in the production of architectural components has shown significant potential to meet the growing demands for customization and optimization. However, there is still a considerable degree of uncertainty regarding how these techniques can be integrated into current construction systems. Considering that concrete is widely used in the construction industry and that cement production is a significant source of CO_2 emissions, it becomes crucial to explore these new technologies to enhance its efficiency.

To adapt digital fabrication to the specific requirements of real-world context, this study explores the application of 3D Concrete Printing (3DCP) within a prefabrication framework in a controlled laboratory setting. Following the development of the extrusion system, a series of prototypes were produced to systematically scale up manufacturing and identify key process control parameters.

Finally, to demonstrate the applicability of 3DCP in complex environments, this paper presents a case study involving a prototype designed for implementation on a coastal rockfill in Póvoa de Varzim, Portugal. The process begins with a 3D survey of the site, followed by the custom design of a set of discretized platforms composed of medium-sized parts and their corresponding connections. This case study validates the feasibility of the technology and methodology for industrial applications, highlighting its potential for adaptable and efficient construction solutions in challenging contexts.

INTRODUCTION

In recent years, advancements in computational design and digital fabrication – particularly through Additive Manufacturing (AM) – have opened new possibilities for creating complex, free-form, and highly detailed geometries that were previously unattainable with traditional construction methods. Despite clear benefits such as the elimination of formwork, reduction in labour costs, decreased material waste, and the potential for mass customization [1], applications in construction industry remain limited more than two decades after initial experimental trials.

Concrete stands as the most widely utilized material in the construction industry, celebrated for its versatility, mechanical strength, and durability. However, its environmental impact is significant, with cement production alone accounting for approximately 10% of global CO_2 emissions [2]. This high carbon footprint is primarily associated with the calcination of limestone and the energy-intensive processes involved in clinker production [3]. Given these challenges, integrating advanced digital fabrication technologies like 3D Concrete Printing (3DCP) presents a viable pathway to improve material efficiency, reduce waste, and optimize both structural and environmental performance.

By enabling precise material deposition, minimizing the need for formwork, and allowing for topologically optimized geometries, AM techniques have the potential to enhance the economic and ecological sustainability of cementitious materials in construction [4].

Recent research by the Architecture, Construction, and Technology Hub (ACTechHub) at the School of Architecture, Art, and Design at the University of Minho aims to bridge the gap between digital fabrication techniques and practical construction applications. This work contributes to the advancement of 3DCP for scalable and efficient construction solutions. The research explores multiple facets of the technology through the prototyping of various customizable architectural components [5].

Each exploratory research uses computational models, particularly parametric design, to simulate and optimize the AM process and the functional purpose of the components to be produced. This approach, facilitates real-time adjustments of the fabrication parameters, improving the adaptability of AM techniques to varying design requirements. Additionally, it allows for greater design flexibility, enabling the generation of customized complex geometries.

To establish a foundation for this research, a preliminary study was conducted focusing on two critical aspects: the material properties and the extrusion system. It aimed to assess the rheological behaviour of the selected material, ensuring its suitability for the 3DCP process, as well as to refine the printing process by evaluating nozzle design, layer adhesion, deposition accuracy, among other parameters related to robotic 3DCP fabrication. These initial experiments provided valuable insights into the interplay between material composition and printing parameters, informing subsequent stages of component development and fabrication.

Finally, presents an extended project as a proof of concept for the use of 3DCP in a pre-existing complex context, demonstrating rapid prototyping through prefabricated modular solutions and customized, reversible assembly strategies.

A fundamental aspect is the application of Design for Assembly and Disassembly (DfAD) principles. DfAD is a strategic approach that optimizes the construction, maintenance, and deconstruction of structures by ensuring that components can be efficiently assembled and later disassembled without damage. In the context of AM, DfAD principles facilitate modular construction techniques, allowing for the replacement of individual components, minimizing waste, and promoting material circularity [6,7]. By incorporating interlocking geometries, reversible connections, and standardized joint mechanisms, DfAD enhances both structural integrity and adaptability. This approach not only streamlines on-site installation but also supports sustainability by enabling material recovery and reuse, reducing environmental impact, and extending the lifecycle of built systems.

CEMENTITIOUS MIXTURE AND EXTRUSION SYSTEM

As previously stated [8], the application of concrete in AM processes relies on the correct combination of two interrelated elements: material and machine. Given the research context, the study of these aspects followed an experimental approach.

Regarding cementitious mixtures, and based on the empirical knowledge established in reference studies [9; 10] the optimal characteristics for 3D printing are evaluated through four key properties that determine their feasibility: (1) Extrudability, (2) Buildability, (3) Workability, and (4) Open Time. However, the use of cementitious mixtures in AM processes presents inherent conflicts between these required characteristics, for example, material fluidity is essential for pumping and extrusion without blockages, yet excessive fluidity may result in weak printed lines, sagging, or even structural collapse.

The success of a printed element is strongly dependent on the interactions between its raw materials. Based on reference formulations, a series of experiments was conducted to test different cementitious mixtures. The initial compositions consisted of simple mortar mixtures (binder and aggregates with water) and were progressively refined through the addition of various admixtures and additives to enhance their performance until achieving optimal printability. Figure 1 illustrates the composition of a cementitious mixture that successfully met the primary 3D printing requirements.

To address the challenge of maintaining consistent production capacity during extended printing sessions, a set of optimized 3D printing mortar mixes developed by Weber - Saint Gobain (Weber 3D 160-1) and Secil (Secil TEK) were tested. These premixed materials, supplied in 25 kg bags, demonstrated good extrudability and buildability. Weber 3D 160-1 allowed for faster layer deposition, while Secil TEK, with its finer granulometry, resulted in an improved surface finish. In terms of mix preparation, Weber's composition required approximately 11% water by weight, depending on the mixer and extruder used, whereas Secil TEK required around 12.5%. For automated water dosing systems, preliminary tests determined optimal flow rates of 265 L/h for Weber and 305 L/h for Secil.

Based on established models [11], the 3D printing process consists of three interconnected stages: (1) mixture preparation, (2) pumping the material to the extruder nozzle, and (3) depositing the material in layers along a predefined printing path. The initial printing setup at the ARENA Laboratory, illustrated in *Figure 2a,* consisted of three interconnected components: (1) a 120-liter planetary mixer, (2) a mortar pump, and (3) a KUKA KR120 2700-2 industrial robotic arm equipped with a tubular end-effector extrusion tool. The connection between the externally positioned mortar pump

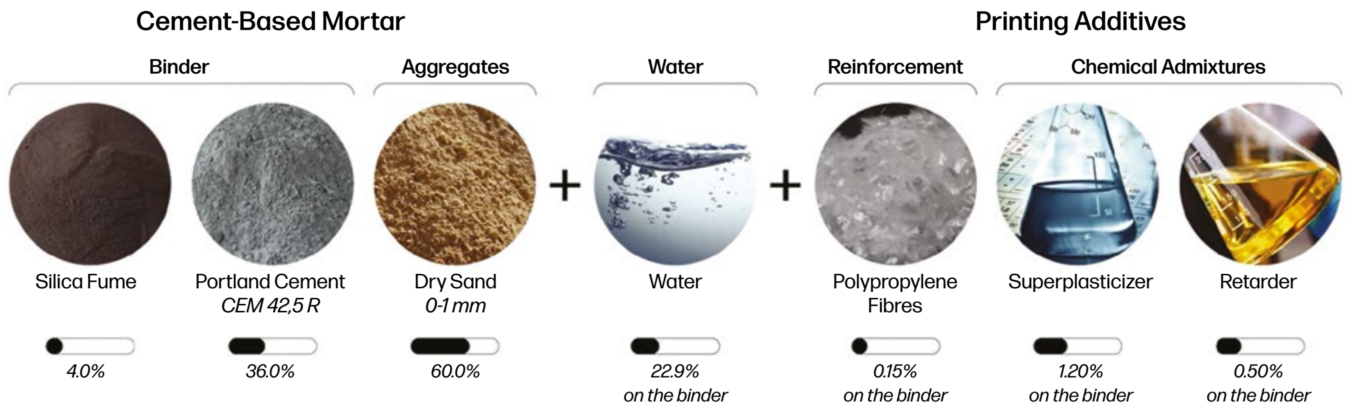

Figure 1: Cementitious mixture recipe.

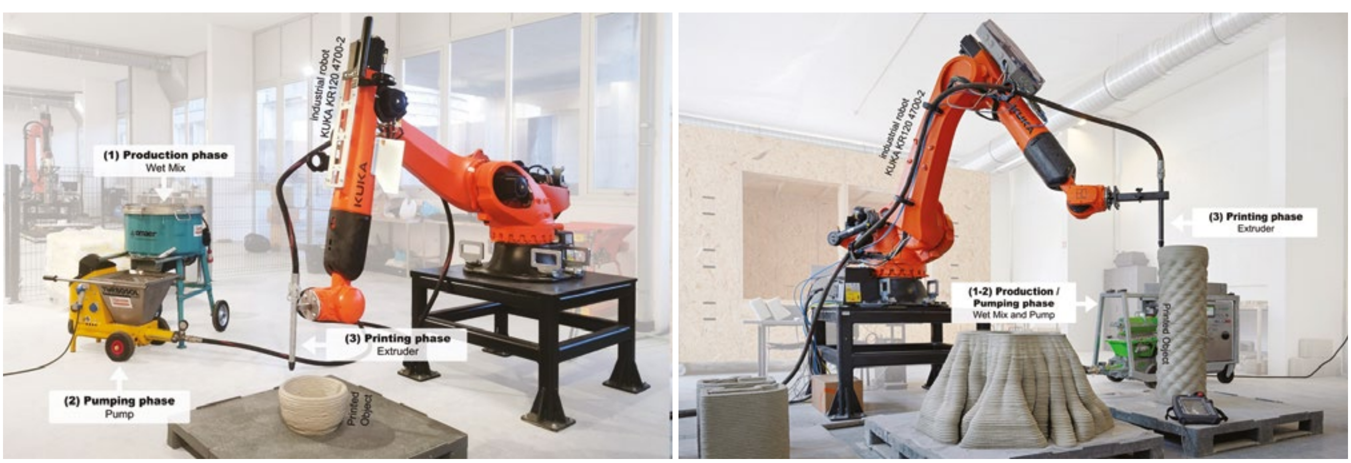

Figure 2: 3DCP printing setups in use at the ARENA laboratory.

and the extrusion tool, mounted on the robotic arm's flange, was achieved through a 25 mm diameter concrete hose.

As shown in *Figure 2b,* this system was later improved by replacing both the planetary mixer (1) and the mortar pump (2) with the MAI Multimix 3D mixing pump, which integrates both mixing and pumping functions into a single unit. Given its continuous horizontal-axis mixing mechanism, the use of pre-packaged dry mixes became essential, allowing precise water dosage adjustments. This solution significantly reduced the workload for operators, as, once correctly configured, the equipment autonomously controlled the entire mixing and pumping process throughout a printing session. Additionally, a modular extrusion tool was developed, incorporating interchangeable extension components that enable greater horizontal and vertical reach of the extruder.

EXPERIMENTAL TESTS

This section outlines a series of preliminary experiments conducted to assess the potential of 3DCP processes. The experimental workflow explored various applications, including structural components, furniture and maritime elements. Through an iterative trial-and-error approach, the main weaknesses of each proposal were identified, and methodologies were developed to overcome their primary constraints. The conclusions drawn from these experiments ultimately informed the definition of the case study.

Mortar tests were carried out using the KUKA KR120 robotic printing setup shown in *Figure 2*. These experiments successfully validated the feasibility of using Weber 3D 160-1 mortar for AM applications, demonstrating its extrudability, buildability, and overall suitability for automated construction. The knowledge gained from these trials was progressively incorporated into subsequent prototype developments. Some of these prototypes will be further detailed in other scientific publications.

Characterization Specimens

A series of extrusion tests were performed using standardized geometries (e.g., straight and inclined cylinders, ovalized specimens with varying curvature degrees, surface filling patterns, etc.) to establish optimal parameters for the extrusion system. These experiments demonstrated that, even with a fixed extruder nozzle (in this case, a 20 mm circular cross-section), substantially different layer geometries could be achieved by adjusting printing parameters.
Key variables included layer height, robot speed, pump flow rate, and geometric constraints such as the inclination of extruded walls relative to the base. *Figure 3* presents a set of four printed specimens where only the layer height was varied (20 mm, 15 mm, 10 mm, and 5 mm), revealing significant differences in the final characteristics of the printed elements. Keeping the extrusion speed and flow constant, layer thickness changed.

Conversely, *Figure 4* illustrates the variation in layer height resulting from a different strategy, in which the robot's movement speed was progressively adjusted during the printing process as a function of the different layer heights. By maintaining a constant pump flow rate, this approach ensured that only the necessary amount of material was deposited, thereby preserving a consistent layer thickness of 30 mm throughout the print.

Demonstration cube

A cube was designed to test various surface patterns and textures through direct manipulation of extrusion paths. Each of its four faces features a distinct variation: (a) a zigzag pattern applied every two layers; (b) another zigzag pattern applied alternately on all layers; (c) a wavy surface; and (d) embossed lettering in low relief. By utilizing attraction points to modulate the spacing within the zigzag patterns, the experiment enabled the precise evaluation of optimal spacing for achieving the intended visual and structural effects. Additionally, the feasibility of incorporating an internal M-shaped reinforcement structure without interrupting the extrusion was assessed. The fabrication of the component, illustrated in *Figure 5*, required approximately 40 minutes.

Concrete column

The scale-up of previously tested geometries required a comprehensive review of printing parameters. A hollow column with a wavy pattern was produced to assess the material's structural viability. The prototype had a 35 cm base diameter, a height of 80 centimetres, and an approximate weight of 80 kg. It was manufactured using a 20 mm extruder nozzle, 10 mm layer height, and a robotic movement speed of 100 mm/s, with a total printing time of about 15 minutes. This type of prototype has potential for integration as a lost formwork system in architectural applications.

The column emerged as an alternative approach to a previous AM ceramic experiment for the columns of a porticoed system originally developed as part of the PhD of João Carvalho [12]. In the initial design, each column consisted of twelve ceramic segments, constrained by the limitations of the ceramic 3D printing process, such as the printer's working area, kiln capacity, and material deformation during curing and firing. To address these constraints, a concrete-based variation was developed. Free from the manufacturing restrictions of ceramic printing, the new column design consists of only two printed segments, each 80 cm high only due to the need for manipulation and placement *in situ*.

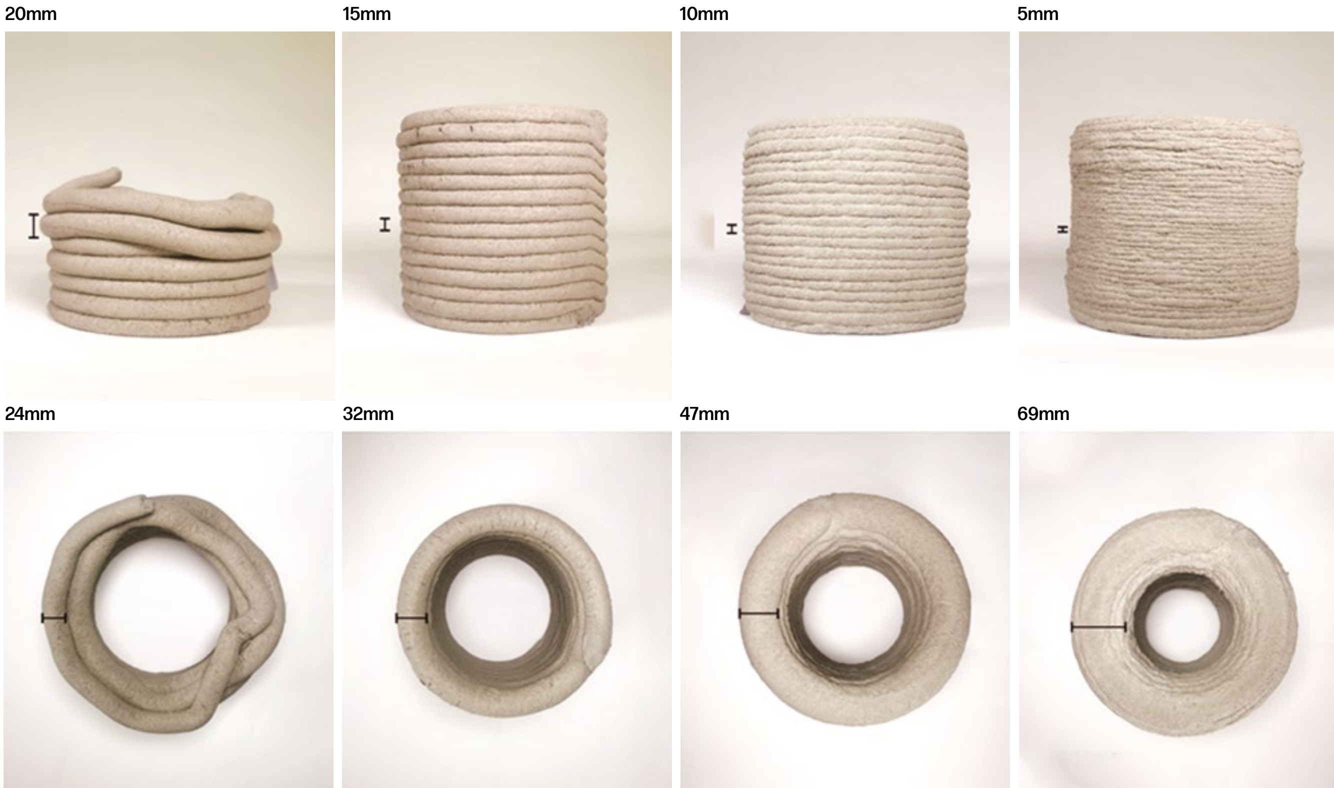

Figure 3: Printed test specimens with varying layer heights.


Figure 4: Relationship between printing speed and Amount of material deposited.

Figure 5: Demonstrator prototype with different textures and internal reinforcement.

Figure 6: Comparison between the ceramic column composed of twelve segments and the concrete column composed of two segments.

Figure 7: Interlocking concrete wavy wall.

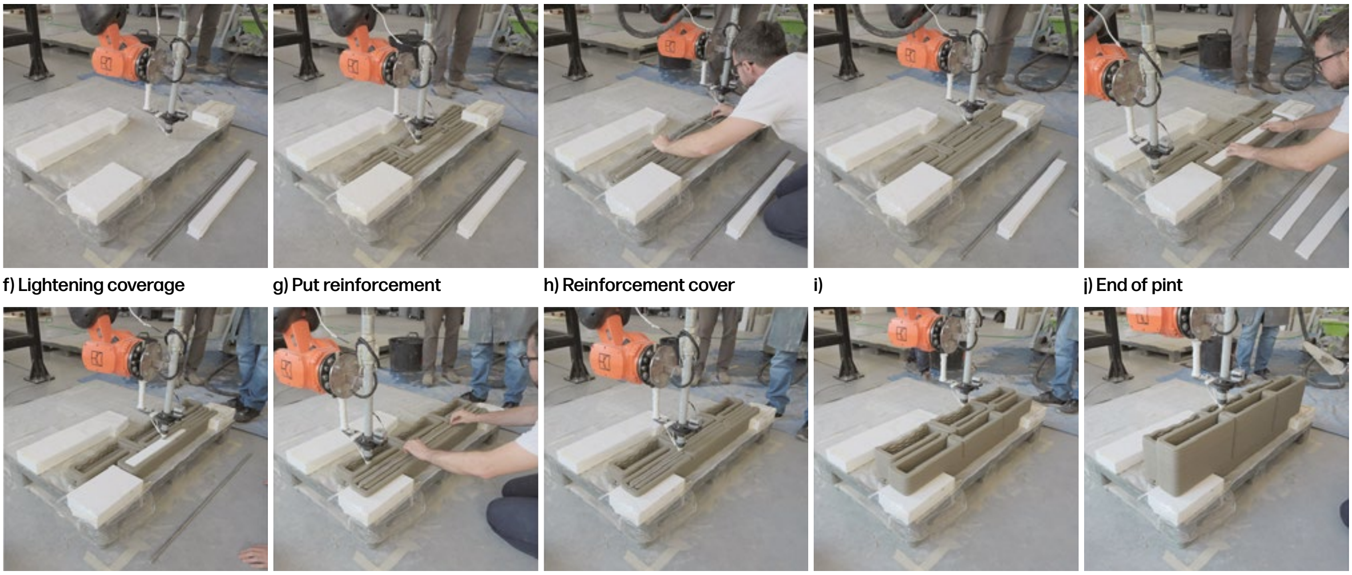

Figure 8: Printing process of a window lintel.

Figure 9: Concrete bench prototype - detail of the seam between layers (left) and full view (right).

Figure 10: Artificial reef prototype printed in ceramic (left) and concrete (right).

Moreover, the concrete column was designed to maintain compatibility with the capital/connection system of the ceramic column with beams. To achieve this, a detailed survey of the ceramic segment geometry was conducted, informing the digital model of the concrete counterpart. The printed segments functioned as integrated formwork for the column. *Figure 6* presents the completed prototype after reinforcement placement and core concreting, alongside the previously developed ceramic column.

Interlocking wavy wall

The concrete wavy wall prototype, shown in *Figure 7*, result from a 3DCP prefabricated masonry system that adheres the following design principles: (1) it consists of a double wall system; (2) stability is mainly ensured by the incorporation of a bidirectional interlocking system into each block, which can be complemented by weak chemical bonds for waterproofing; (3) provides the corrugated surface finish on the exterior; (4) supports the application of an interior wall covering; and (5) it is designed to be lightweight and easily transportable, allowing assembly and disassembly by a single operator.

Beyond exploring the 3DCP process, the prototype aims to achieve a high level of reversibility, aligning with DfAD principles. Additionally, the interconnected internal voids can be utilized for routing infrastructure or for the insertion of insulation materials, enhancing the wall's thermal and acoustic performance.

To address a common limitation of 3D printing – the creation of lintels for windows or doors – ongoing research has focused on integrating reinforcement and light weighting strategies during the printing process. The image below (*Figure 8*) step-by-step illustrates the fabrication of an 80 cm-wide lintel, in which reinforcement bars were embedded in the lower section, while polystyrene inserts were incorporated to reduce weight.

Urban furniture

The design of the concrete bench, developed in collaboration with students Pedro Costa and Ricardo Faria as part of a training course on Robotic Fabrication in Design, Architecture, and Construction, presents a practical application of previously tested concepts. Following a parametric design methodology that allows customization based on desired characteristics, the bench was tailored to accommodate human morphology. The dimensions were constrained by the 1.2 × 1.2 meters printing area, and the piece was designed with a bipartite contour: (1) the lower surface remains regular, while (2) the upper surface features a textile-like texture generated through the zigzag manipulation of extrusion paths. Internally, a reinforcement structure was integrated, connecting both surfaces and providing the necessary support for the waved upper section. During the preparation, the contours and internal reinforcement were fused layer by layer, creating a continuous extrusion path from the first to the last layer. The prototype was printed in a rotational orientation of 90° relative to its final position (*Figure 9*).

Artificial reef

Differential growth algorithms were proposed as design principles to design artificial reefs to be 3DCP manufactured, enhancing marine biodiversity through bioinspired complexity. By leveraging differential growth modelling in Grasshopper 3D, structures were designed with intricate, porous geometries that mimic natural reef formations, providing cavernous pocket spaces for marine species to inhabit, hide, and reproduce [13; 14]. These artificial reef structures align with karst formations and natural reef environments, which have been shown to foster high levels of biodiversity by creating numerous ecological niches for marine organisms [15].

AM techniques have been particularly advantageous in this context for precise fabrication of bioinspired structures using eco-friendly, marine-compatible materials, ensuring long-term stability and integration within the underwater ecosystem [16]. Building upon previous small-scale ceramic artificial reef prototypes as described by C. Lange *et al.* [17], a similar geometry was fabricated in concrete, demonstrating the scalability and structural integrity of AM techniques for marine conservation. The prototype, shown in *Figure 10*, features a hexagonal base measuring one meter in diameter, a height of 50 centimetres, and a total weight of approximately 300 kilograms, making it suitable for deployment in marine conditions. When deployed in marine environments, these porous structures provide essential shelter and protection for various marine species, supporting the natural development of ecosystems in artificial habitats.

ROCKY PONTOON PLATFORM SYSTEM

Coastal and river erosion have emerged as critical challenges for cities located along shorelines worldwide, driven by both human activities – such as the continuous development of coastal areas and rising average sea levels – and natural processes, including wave and tidal action. This phenomenon primarily results from the gradual displacement and transport of coastal sediments due to oceanic forces, such as currents and tides, leading to shoreline retreat and the progressive loss of land to the sea [18].

To mitigate these impacts, engineers have traditionally constructed large-scale structures such as breakwaters and seawalls, composed of natural stone or concrete elements arranged to effectively dissipate wave energy [19]. These structures often occupy valuable coastal zones – such as beaches, urban waterfronts, or riverbanks – that are also used for recreational and occupational activities, including fishing and walking. Despite their protective role, the irregular shapes and voids within these structures can pose safety risks, and their complex nature makes non-intrusive rehabilitation or enhancement technically challenging.

Nevertheless, significant technological progress has been made in computational design, photogrammetric surveying, and 3D printing techniques [20]. On one hand, advanced digital tools and 3D scanning technologies allow for precise documentation and modelling of complex environments that were once difficult to capture accurately. On the other hand, 3DCP enables the mass production of unique, customizable geometries, streamlining construction processes in highly complex contexts. This approach eliminates the need for bespoke formwork for each individual geometry and allows for the creation of hollow components. When combined with structural and formal optimization algorithms, these innovations can significantly reduce raw material usage, component weight, and the size of required structural elements, while also enabling the internal structure to be tailored to specific functional requirements.

Intervention proposal

Recognizing the limitations of 3D-printed structures in fully replacing the heavy rockfill that constitutes breakwaters and riverbanks, a strategic approach was developed to implement a modular platform system designed specifically for these irregular surfaces. The primary objective of this system is to provide functional versatility, supporting the integration of walkways, recreational areas, fishing spots, sea-view platforms, urban furniture, and other infrastructure elements that promote the safe and accessible use of these environments (*Figure 11*).

The adoption of digital design and advanced manufacturing technologies is driven by the need to respond effectively to the site's inherent geometric complexity. Additionally, the intervention is guided by the principles of DfAD, ensuring that the system remains temporary, reversible, and reusable. This methodology minimizes intrusive or destructive modifications to the existing structures, thereby preserving both their structural integrity and the surrounding environmental context.

To achieve a precise fit with the irregular topography of breakwater rocks, photogrammetry technologies were used to capture detailed digital models of the rock geometries. These high-resolution models guided the development of generative design algorithms, facilitating the creation of platform structures that integrate seamlessly with the site's contours. On the production side, 3DCP was employed to fabricate self-supporting segments that accurately replicate the digital geometries, minimizing the need for mechanical or chemical anchoring.

From an ecological perspective, we argue that AM processes can provide innovative solutions to support local marine biodiversity. This artificial platforms, designed with hollow interiors, feature internal structures that can be optimized to fulfil two key objectives: (1) enhancing the mechanical strength of the components to withstand the dynamic forces of ocean waves; and (2) creating internal cavities with varying textures and dimensions to promote the establishment of native marine life, fostering local biodiversity through the creation of microhabitats and ecological niches conducive to the growth of marine flora and fauna.

Methodology

The development process for this study was structured in key stages, as illustrated in *Figure 12*. The first stage involved conducting a photogrammetric survey of the intervention site. This was followed by the post-processing of the 3D model generated from the survey, allowing for a detailed representation of the site's topography *(Digitization)*.

In the third stage, design considerations were addressed using a parametric workflow implemented in Grasshopper. This approach facilitated the generation of design solutions based on predefined manufacturing constraints – such as maximum allowable inclination angles – and additional parameters, including the intended programmatic functions and the overall architectural concept (*Form generation)*.

The subsequent two stages focused on fabrication. Initially, in the fourth stage, print path generation was carried out for each individual platform, incorporating the design of internal structural elements. This was followed by the production phase, conducted in a controlled laboratory environment using a 3DCP extrusion system mediated by a robotic arm *(Fabrication process)*.

Finally, the prefabricated components would be transported to the intervention site, where in-situ post-tensioning would be performed to achieve the final structural assembly. This step has been replaced by laboratory testing *(Laboratory assembly)*.

Implementation

The prototype production process began with the selection of the intervention site. After comparing several urban waterfront areas, the study identified the Breakwater of the Póvoa de Varzim Lighthouse (Oporto, Portugal) as the chosen case study. The specific intervention area within this site was chosen based on observed fishing activities, the rugged topography, and the safety hazards associated with accessing the area (elevation difference). *Figure 13* highlights the selected location.

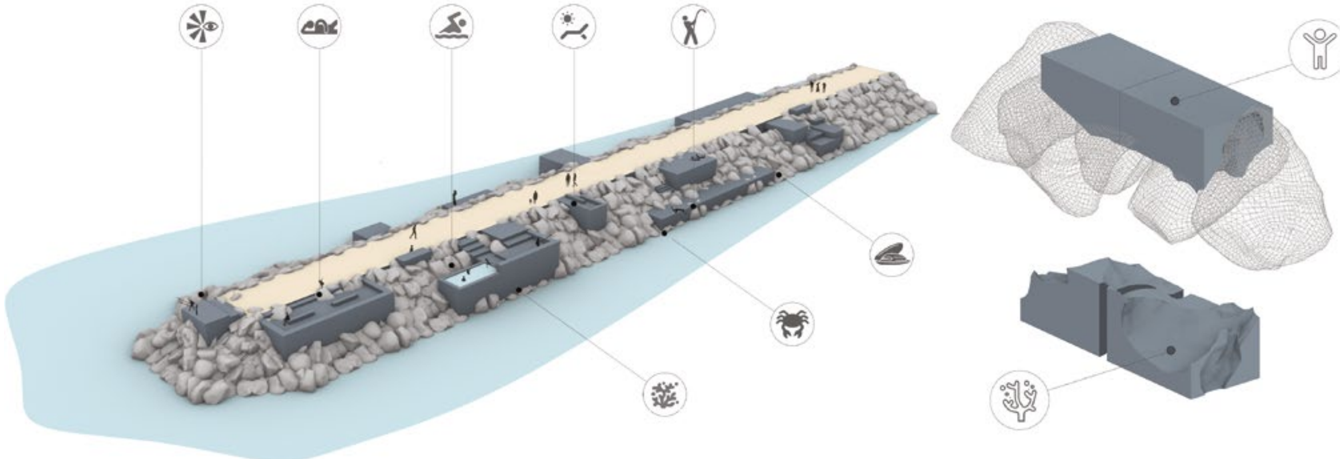

Figure 11: Occupation scheme of rocky breakwaters, with custom-made precast 3DCP components.

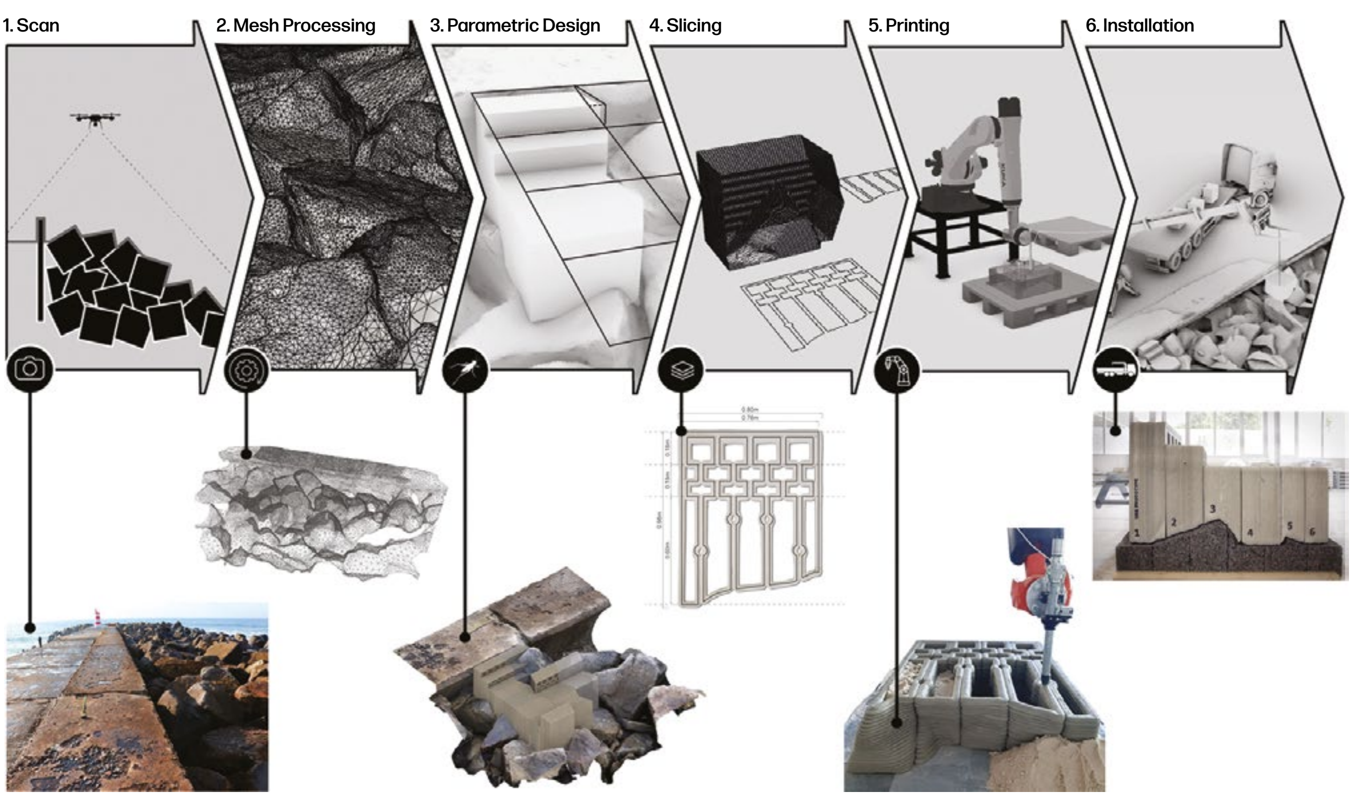

Figure 12: Scheme of the working methodology.

Digitization

Photogrammetry was chosen for 3D surveying of the breakwater area due to its high resolution, suitability for outdoor environments, and cost-effectiveness. The survey was conducted by a single operator using a mid-range digital camera, capturing approximately 120 photographs. Each image was taken while moving around the selected area of interest in circular paths, varying both the distance from the rocks and the camera angle to minimize blind spots and avoiding factors such as self-shadowing or reflections that could affect the quality of the mesh construction *(Figure 14a).*

After testing various photogrammetry software, *PhotoCatch* provided the fastest and highest-quality reconstruction, processing 3.5 m² in about 30 minutes. The resulting mesh was then imported into *MeshLab* for post-processing, where the *quadratic-edge collapse* algorithm reduced the mesh size by 40%, while maintaining a deviation of less than 1 cm. This reduction proved essential to optimizing the efficiency of subsequent design phases, ensuring that the necessary geometric accuracy was preserved for precise, site-specific fabrication (*Figure 14b*).

Form generation

The geometric definition process for each slab was developed through a parametric workflow that can be adapted to any section of the breakwater. This system begins by delineating an area of interest, onto which a rationalized grid is superimposed, with each cell representing a discrete module of the platform. Various topological grid configurations were analysed to identify the optimal arrangement that balances local support, effective interlocking behaviour, and geometric suitability for 3DCP fabrication.

Figure 15 illustrates the generative scheme of the platform design. Using the 3D model obtained through the digitalization (a), the process began with the establishment of a rationalized grid with 80 × 80 cm cells over the area of interest (b). Then, a genetic algorithm was employed to adjust the placement of the grid cells, optimizing their location to maximize contact with the underlying rock formations. The module positions were fixed to ensure each unit maintains an adequate load distribution (c). To enhance structural interlocking between adjacent modules, the vertical edges were modified by introducing mid-point offsets, creating a zigzag pattern that promotes mechanical interlocking (d). Subsequently, further subdivision was applied to limit surface inclinations, ensuring that all components meet the manufacturability constraints of the 3DCP process (e). This approach resulted in modules of varying heights (20 cm and 30 cm), all within the dimensional and structural limits of the printing equipment and with a manageable weight to allow the transportation.

The generated grid defines the upper perimeter of each slab. To derive the volumetric configuration, a point cloud was created (f) and projected along the z-axis onto the 3D mesh of the site survey, populating the area of each module (g). A *Delaunay triangulation* algorithm was then applied to generate a mesh for each slab, followed by a quadratic reconstruction of the meshes faces to correct surface imperfections (h). Finally, the mesh was extruded to achieve the desired height, corresponding to the functional role of each module within the platform (i). This method was preferred over direct Boolean operations between the extruded geometry and the terrain mesh to avoid potential issues during print preparation.

Each slab's geometry is unique, shaped by four key criteria: (1) it conforms precisely to the geometry of the supporting rocks, ensuring a secure fit; (2) it interlocks seamlessly with neighbouring modules through custom-designed joints; (3) it fulfils specific programmatic functions on the surface, such as circulation pathways and resting areas; and (4) it contributes to local biodiversity by incorporating internal cavities that create new habitats for marine species. *Figure 16* presents a 3D simulation of part of the platform to be produced.

Fabrication process

The fabrication of the prototype required a preparatory phase in which the 3D models of each component were translated into a set of toolpaths guiding the robotic extrusion process. In polymer-based AM, slicing software typically automates this step, however, concrete printing introduces additional challenges that necessitate a more controlled approach. Given that the contact geometry with the breakwater rocks was unique for each piece, a custom script was developed in Grasshopper to assist in generating the extrusion paths. Additionally, the optimal printing orientation of the components was analysed. Preliminary tests determined that printing the elements in a lateral position, rotated 90° from their final in-situ placement, would yield the best structural performance and minimize deformations.

The generation of contour curves for each platform component followed a three-step process. First, a series of horizontal planes were defined, spaced according to the layer height, which was set at 10 mm. Next, the intersections between these planes and the 3D model of each component were computed, resulting in a sequence of closed curves outlining the external boundaries. Finally, these curves were offset by half the extrusion width (approximately 35 – 40 mm for a 20 mm nozzle) to ensure a continuous and stable printing path. After analysing the generated toolpaths, the base orientation of each piece was defined to reduce deformations caused by inadequate support for upper layers.

The next step involved designing the internal structure of each component. A parametric approach was adopted to accommodate different functional requirements, including staircases, circulation areas and seating elements, while ensuring sufficient internal support for the upper layers. The internal structure followed a cellular pattern with three primary objectives: (1) enhancing the structural resistance of the printed element, (2) creating voids that facilitate wave energy dissipation, and (3) incorporating morphological features with textures and concavities to promote the attachment of native marine flora and fauna. This proposal resulted in a design of an internal alveolar structure that can be freely adjusted, ensuring the necessary continuities between the elements.

Figure 17 illustrates three distinct types of cross-section that configure the platform access ladder. For instance, the leftmost section features four cells of varying heights. Their alveolar boundaries are aligned horizontally to ensure adequate support for upper layers. Additionally, duplicated vertical lines were incorporated to enhance the component's overall strength and provide a continuous printing path with well-aligned layer seams.

Finally, a connection system was integrated to enable modular assembly and disassembly. To maintain structural flexibility and allow for reversibility, chemical bonding between elements was avoided. Instead, post-tensioning systems with steel cables were used during assembly. To accommodate this approach, voids were strategically placed within the printed modules to allow for cable passage. These cables were arranged perpendicularly to the printed layers and tensioned to apply compressive forces, effectively unifying the platform and reducing tensile stresses. *Figure 18* illustrates the modular components and simulates the assembly process.

Based on prior calibration, the optimal printing parameters included a layer height of 10 mm, a 20 mm extrusion nozzle and a printing speed of 100 mm/s. The pump pressure was adjusted to maintain a consistent extrusion width of approximately 40 mm throughout the process. *Figure 19* illustrates the printing of one of the parts, using sand as support material for the steeper surfaces.

Laboratory assembly

Since on-site positioning was not permitted, a laboratory-based validation of the concept was conducted by replicating the geometry of the digitized rocks. This artificial topography was created through a milling process using a series of black agglomerated cork blocks (each measuring 1000 × 500 × 320 mm), shaped with the assistance of a robotic arm equipped with an industrial spindle. *Figure 20* illustrates this process.

The milling procedure was carried out in two stages: (1) Initially, a rough cut was performed using a terraced approach, with cutting paths generated in Fusion 360 and subsequently imported into Grasshopper for KRL code generation. This process, which took approximately 12 hours, was executed using a 12 mm flat-end mill, with an 8 mm stepover and a 20 mm stepdown; (2) The final finishing stage was then applied. In this phase, a 12 mm ball-nose end mill was used, following parallel toolpaths spaced 6 mm apart in both orthogonal directions of the surface. These toolpaths were directly generated in Grasshopper by interpolating surface points with a 20 mm offset. To enhance the surface quality, the tool orientation was determined by the normal vector of the surface at each interpolated point. *Figure 21* presents the fully refined cork base.

The final stage involved positioning the six printed components onto the previously milled cork base. Given that each printed component weighed between 150 and 300 kg, depending on its size, their transport and placement required the use of a forklift or a crane system. A rubber strip was inserted between each adjoining module to absorb potential irregularities and prevent direct contact between elements. Once all components were positioned, steel cables were passed through the designated conduits and tensioned using a torque wrench. *Figure 22* depicts the completed prototype.

CONCLUSION

This research demonstrates the versatility and efficiency of 3DCP, emphasizing its potential to respond in complex real-world context. By integrating advanced digital fabrication techniques with prefabrication logic, the study highlights the adaptability of cementitious AM to diverse applications, from architectural systems to coastal infrastructure solutions.

For instance, the production of C*oncrete column* prototype, showcases key advantages in terms of efficiency, sustainability, and adaptability. In addition to being able to obtain geometries that are impossible to achieve with traditional methodologies, the use of this technology to produce the integrated column formwork reduces material waste and the labour required. Furthermore, the concrete column maintains the topologically optimized geometry of the ceramic column, yet produces it in a 95% faster printing time. Adding to this the need for curing and firing the ceramic material, we conclude that we have achieved a significantly improving construction speed, reducing the time gap between production and on-site assembly.

The *Rocky pontoon platform system*, highlights the potential of 3DCP in coastal environments, demonstrating the feasibility of digitally fabricated solutions for adapting to complex terrains. Key advantages include the elimination of formwork, a 42% weight reduction through strategically placed voids that enhance transportability and installation feasibility, and custom-fit fabrication using

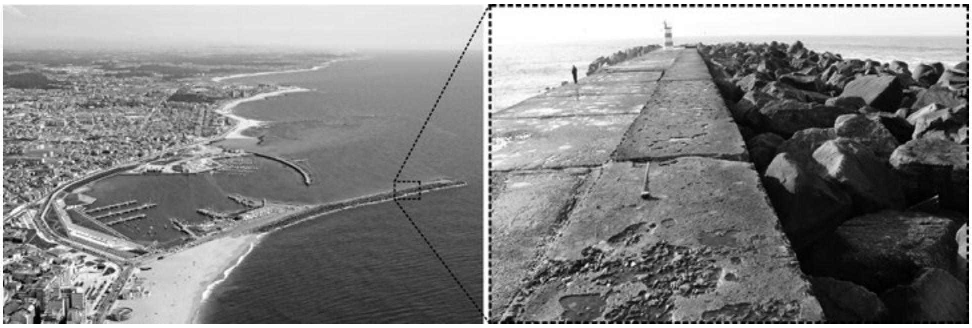

Figure 13: Location of the case study – Póvoa de Varzim Lighthouse Pontoon, Porto, Portugal.

a)

b)

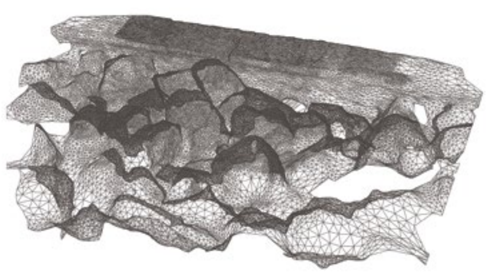

Figure 14: Example of four photos used for local photogrammetry (a) and the generated mesh (b).

Figure 16: 3D simulation of the designed platform, highlighting the section to be produced.

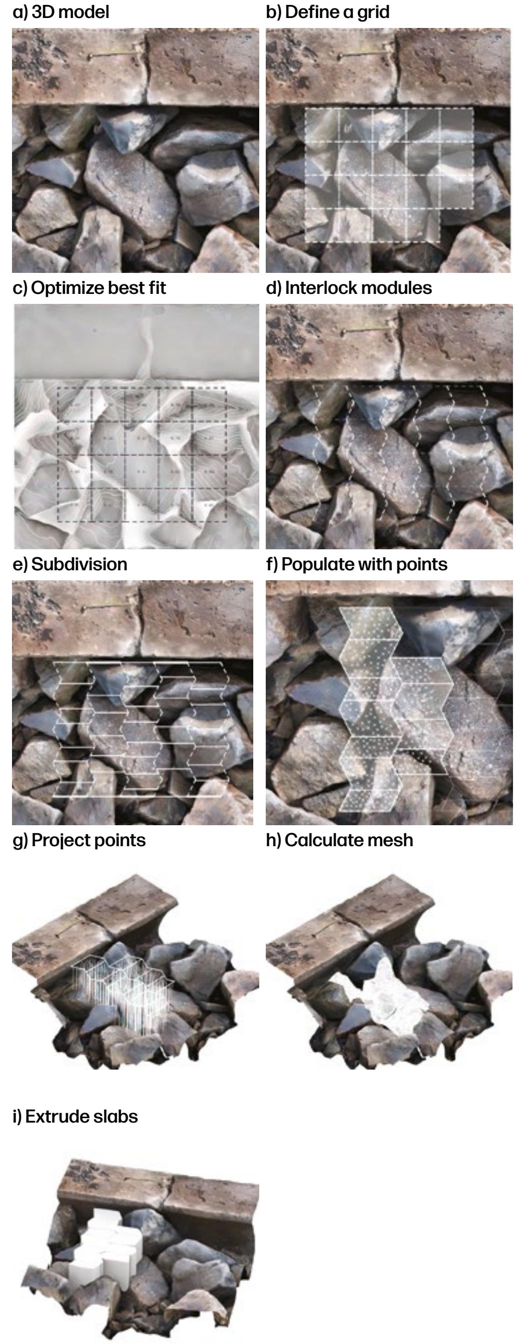

Figure 15: Generative scheme of a platform.

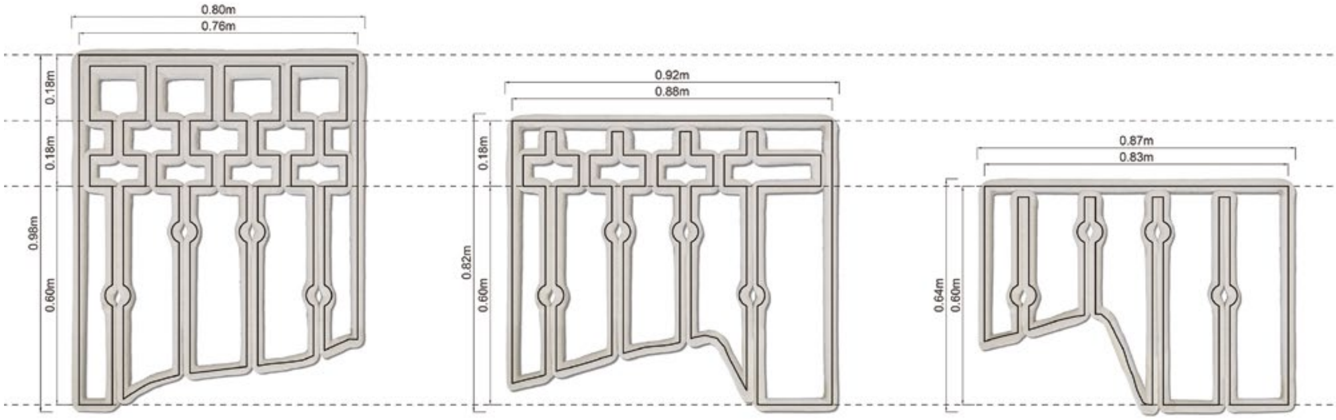

Figure 17: Different infill strategies to reinforce printed components and support upper layers.

Figure 18: Exploded view of the different sections of the printed modules.

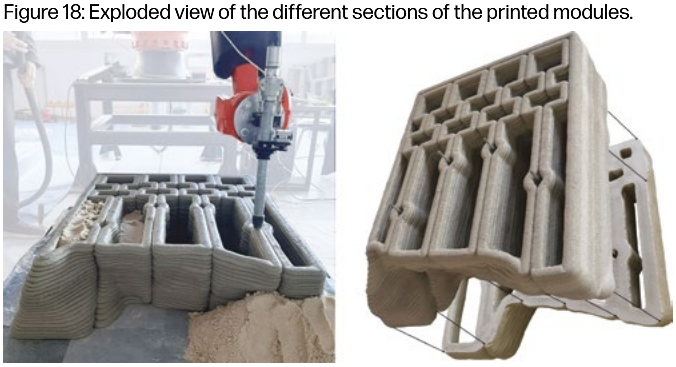

Figure 19: Printing process of a full-scale prototype (a) and post-tensioned assembly of two printed sections (b).

Figure 20: Milling process of the cork base.

Figure 21: Artificial topography in cork produced through laboratory milling.

Figure 22: Fully assembled prototype in the ARENA Laboratory after post-tensioning application.

Scan-to-3Dprint methodology to enable site-specific adaptations. Additionally, the system was designed following DfAD principles, ensuring modularity, reusability, and long-term adaptability.

The final prototype successfully demonstrated full structural functionality without requiring chemical bonding between components, allowing for assembly and disassembly without causing damage to the structure or its surrounding environment. Due to its modular nature, individual components can be easily replaced by releasing the post-tensioning system, inserting the new element, and reapplying tension to the steel cables. Ultimately, the components can be reused after disassembly, enabling seasonal deployment and reinstallation year after year. Furthermore, the design avoids mixing different materials, ensuring that at the end of its lifecycle, each part can be ground and recycled as aggregate in new cementitious mixtures. This approach enhances the sustainability of the proposal by promoting circular economy principles.

All prototypes validate the application of 3DCP in architectural and infrastructural systems, reinforcing its role in accelerating construction processes, minimizing material waste, and enabling mass customization. It also suggests that robotic 3DCP prefabrication can contribute to construction efficiency, offering scalable and sustainable alternatives for contemporary architecture and engineering. Future research should further investigate the mechanical performance, durability, and long-term resilience of these printed structures, as well as expand the integration of alternative, low-carbon cementitious materials to enhance environmental sustainability. By continuing to refine these methodologies, 3DCP can play a transformative role in shaping more adaptable, efficient, and sustainable built environments.

ACKNOWLEDGEMENTS

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TWO SUSTAINABLE BUILDING SYSTEMS: THE IMPACT OF SHRINKAGE ON NATURAL MATERIALS IN ADDITIVE MANUFACTURING

Tatiana Campos
Paulo J. S. Cruz
Bruno Figueiredo

The growing demand for sustainable building solutions requires a shift from conventional building materials to biodegradable, recyclable and reusable alternatives. A comparative analysis of two architectural systems was undertaken using natural materials – biodegradable, recyclable and sustainable – such as cellulose, which was combined with other raw materials. This work explores the use of additive manufacturing (AM) technologies – Paste Extrusion Modelling (PEM) – to produce individualized components, using three-dimensional modelling programs such as Rhinoceros and Grasshopper to develop the digital design. It compares a set of mixtures, analyses a range of printing specifications, to evaluate the opportunities as well as potential limitations of AM, as well as those due to drying and, finishing in.

INTRODUCTION

The use of natural, sustainable, and biodegradable materials in architecture is essential for reducing the consumption of inorganic materials and, consequently, minimizing environmental impact, thereby promoting more energy-efficient buildings. According to González & García Navarro (2006) [1], the adoption of materials such as wood, ceramics, cork, and natural fibers not only has a low environmental impact but also significantly contributes to the reduction of CO_2 emissions into the atmosphere. With the increasing demand for sustainable construction solutions, the integration of eco-friendly materials in architecture represents a fundamental strategy for building a more resilient and environmentally re-sponsible future. [2]

The present article aims to develop a comparative study on the analysis of shrinkage architectural components made from natural-origin materials. The comparative study involves the analysis of different architectural systems, designed for distinct purposes and utilizing various material compositions. Kusudama is a self-supporting wall composed of a set of individual hexagonal blocks with distinct internal geometries (Figure 1a). Designed as a proof of concept inspired by traditional origami, often used as decorative elements or in architectural applications, the structure consists of two types of differentiated geometric blocks: triangular negatives and pentagonal positives. [3-6] The combination of these elements generates a wavy pattern with topographical variations, imparting innovative aesthetic and functional properties to the wall. Pulpbaffle is a self-supporting wall composed of a set of individual undulating blocks with acoustic properties (Figure 1b). Developed based on the concept of sound propagation waves, the undulating geometry is generated from a set of variable parameters, which, when manipulated, allow a differentiated response to the environment, adjusting to the absorption or reflection of sound according to the user's needs. [6]

The study includes a comparative analysis of the material mixtures used during the AM process, drying, shrinkage index, and, finally, the finishing of the various blocks.

MATERIAL

Cellulose (Figure 2) is a natural, organic, biodegradable, and recyclable polymer com-posed of glucose chains, serving as the primary structural component of the cell walls of plants, algae, and oomycetes. It is derived from Eucalyptus globulus, ...an important plantation species in subtropical regions, including southern Europe (Spain, Portugal)... [7], selected for its high-quality fibers for paper production, as 50% of its fibers consist of cellulose. It is the most abundant biopolymer in nature and has extensive applications across various sectors, including the paper, textile, pharmaceutical, and construction industries.

The cellulose production process consists of three main stages: (1) the cultivation of Eucalyptus Globulus through forest plantation; (2) the harvesting of the wood, during which the logs undergo rigorous inspection, are debarked and fragmented into particles of controlled dimensions, referred to as chips, shavings, or wood flakes; and (3) the production of cellulose pulp, which involves a cooking process aimed at individualizing the cellulose fibers, facilitating the separation of lignin to obtain raw pulp with a brownish hue. Subsequently, the raw pulp undergoes a bleaching process using a solution of caustic soda and sodium sulphide. [8] All the constituent elements in eucalyptus are utilized, from the leaves to produce essential oils, cellulose for the production of paper and lignin, a macromolecule, for the production of thermal insulation foams. The reuse of all the elements eliminates possible waste.

PRINTING MIXTURES

To produce both prototypes, a mixture made up of a set of materials in different proportions was developed, as shown in Table 1. The preparation of the mixtures results in the combination of 9 to 10% of corn starch (w/v) (VRW, Radnor, PA) with 60 to 64% of water (v/v). To produce the pulpable mixture, in addition to the starch, 3% gelatine and 2% black cork agglomerate are added. After homogenising the materials, heat them with vigorous stirring until a highly viscous hydrogel is formed. After the temperature of the hydrogel has dropped, 25 to 27% micronized cellulose (w/v) is added in small amounts until a completely homogeneous mixture is formed. Each natural material was properly selected with the aim of developing a natural, biodegradable and sustainable mixture capable of being returned to the environment. The use of local materials was also taken into consideration, thus reducing possible environmental impacts associated with transport and production. [3-6]

Table 1: Comparative analysis between the Kusudama and Pulpbaffle mixture.

	Kusudama	Pulpbaffle
Water	64%	60%
Starch	9%	10%
Cellulose	27%	25%
Gelatine	-	3%
Cork	-	2%

The mixtures used in the production of both architectural systems have been analysed and, it can be concluded that the Pulpbaffle mixture was enhanced by incorporating new ingredients and adjusting the proportions of the base components. This modification was necessary to improve the final quality of the produced elements.

PRINTING SPECIFICATIONS

When analysing the various printing parameters to manufacture the prototypes, visible differences were observed, as shown in table 2.

Table 2. Comparative analysis between the Kusudama and Pulpbaffle printing specifications.

	Kusudama	Pulpbaffle
Printing pad	One direction	Two directions
Velocity	20mm/s (100%)	14mm/s (70%)
Air pressure	3bar	4.5bar
Nozzle	3mm	5mm
Internal Structure	Yes	No
Plate	Smooth surface	Perforated surface

The first aspect to consider was the printing path. In the Kusudama blocks, the presence of three distinct surfaces – internal, external, and structural – resulted in multiple

Figure 1: The picture on the left is the Kusudama wall (1a) and on the right is the Pulpbaffle wall (1b).

Figure 2: Micronized cellulose provided by RAIZ – Institute Research of Forest and Paper.

Figure 3: a) Study that determinates the maximum degree of curvature supported by the cellulose. b) Internal walls of the Kusudama Blocks.

Figure 4: Pulpbaffle block after printing.

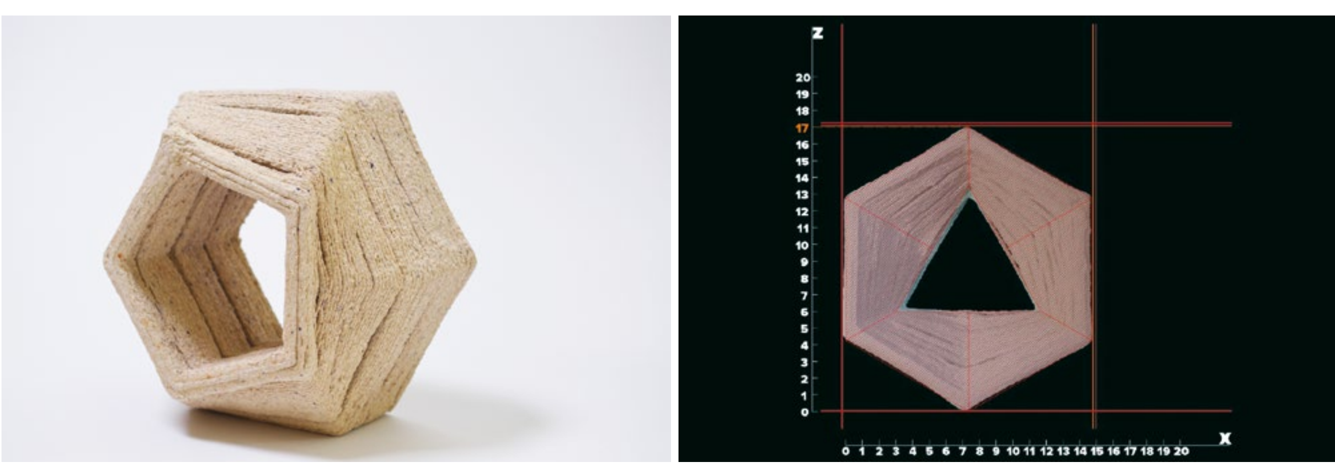

Figure 5: Shrinkage of Kusudama blocks. Delamination between layers due to evaporation of water.

interruptions throughout the layers, leading to material accumulation in the seam regions of the geometries. In contrast, the Pulpbaffle blocks were designed with a continuous geometry, allowing for the inversion of the printing path between layers, thereby enabling the use of two printing directions. Another critical factor was the printing speed. For the Kusudama blocks, a speed of 20 mm/s was selected, whereas for the Pulpbaffle blocks, a reduced speed of 14 mm/s was chosen to enhance the final quality of the piece and minimise wall deformations. Furthermore, due to modifications in the composition of the mixtures, it became necessary to increase the air pressure applied during the extrusion process in the Pulpbaffle blocks, as well as to enlarge the diameter of the extrusion nozzle. Another factor considered was the use of a perforated surface, which facilitated the drying process, promoted uniform material shrinkage, and prevented undesired deformations.

PRINTING LIMITATIONS

Both prototypes under study are modular wall systems; however, the blocks are arranged differently and exhibit distinct geometries. The Kusudama blocks consist of linear geometries, whereas the Pulpbaffle blocks are composed of undulating geometries. When analysing the Kusudama blocks, it was observed that they feature walls with varying inclinations, making it essential to determine the maximum curvature permitted by the material. To address this, a set of conical geometries was developed, varying the curvature of the walls (Figure 3a), leading to the determination that the maximum allowable wall curvature for the Kusudama blocks is 30º.[3] Additionally, a set of internal walls (Figure 3b) was incorporated into the digital model to connect the inner and outer geometries, reducing deformations caused by the drying process and providing structural support for the inclined walls.

Regarding the Pulpbaffle blocks, it was essential to determine the most effective way to prevent potential wall deformations, thereby ensuring better overlap between the different blocks that compose this architectural system (Figure 4). To achieve this, a black cork agglomerate additive was incorporated into the mixture, aiming to reduce layer shrinkage due to water evaporation and enhance the material's acoustic performance. Furthermore, to ensure greater consistency between the digital model and the fabricated model, minimum and maximum dimensions were established for the base and height of the block. The greater the height, the higher the susceptibility to wall deformation due to the material's viscosity and the pressure exerted during the extrusion process.

DRYING

Considering that the construction systems under study were produced using different mixtures and printing parameters, the material's behaviour during the drying process also varies, which indirectly resulted in different shrinkage rates. When analysing the drying process of the Kusudama blocks, delamination between layers and wall deformations were quickly observed. This is attributed to the high-water content in the mixture, the absence of a natural adhesive to effectively bond the layers, and the use of a small extrusion nozzle. As water evaporates during drying, the material contracts; the higher the water content, the greater the shrinkage. As shown in Figure 5, the shrinkage rate of the blocks in height is 10%, whereas at the base, it is only 1%. Although the block retains its base dimensions, it tends to shrink at the top due to the absence of a drying system that could indirectly mitigate the occurrence of potential deformations.

It was quickly concluded that the mixture used for the AM of the Kusudama blocks missing certain essential ingredients. Therefore, for the production of the Pulpbaffle blocks, a refined mixture was formulated, consisting of a liquid component, a binder, a fibrous element, and an aggregate, ensuring superior final quality. Additionally, a drying system was developed, comprising two perforated plates connected by an extendable spring (Figure 6). The block is printed onto one of the bases and left to air-dry for approximately two hours, allowing the gelatine to begin solidifying and bonding the layers together. Once the drying system is assembled, the block is placed inside a drying chamber and rotated multiple times to ensure uniform drying.

After 24 hours, the drying system is disassembled, as the outer surface is already dry, allowing the block to continue drying internally. The complete drying process for a single block takes 36 hours. Analysing the shrinkage data presented in Figure 7, it was observed that the shrinkage rate in height is 19%, whereas at the base, it is 3%.

DISCUSSION

By analyzing the mixture and drying method used for the AM of the different blocks that constitute each construction system, it was concluded that the final quality primarily depends on the ingredients forming the mixture. The higher the water content, the greater the delamination between layers. The introduction of gelatin into the mixture also has a significant impact on the quality of the block, as it helps prevent delamination between layers. However, due to its adhesive properties, it increases the shrinkage rate in the block's height, rising from 10% to 19%. Nevertheless, this adjustment ensures greater stability between the digital model and the fabricated model. [3-6]

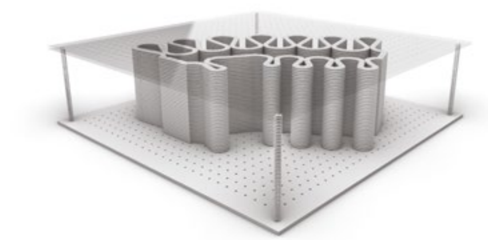

Figure 6: Drying system developed for drying Pulpbaffle blocks.

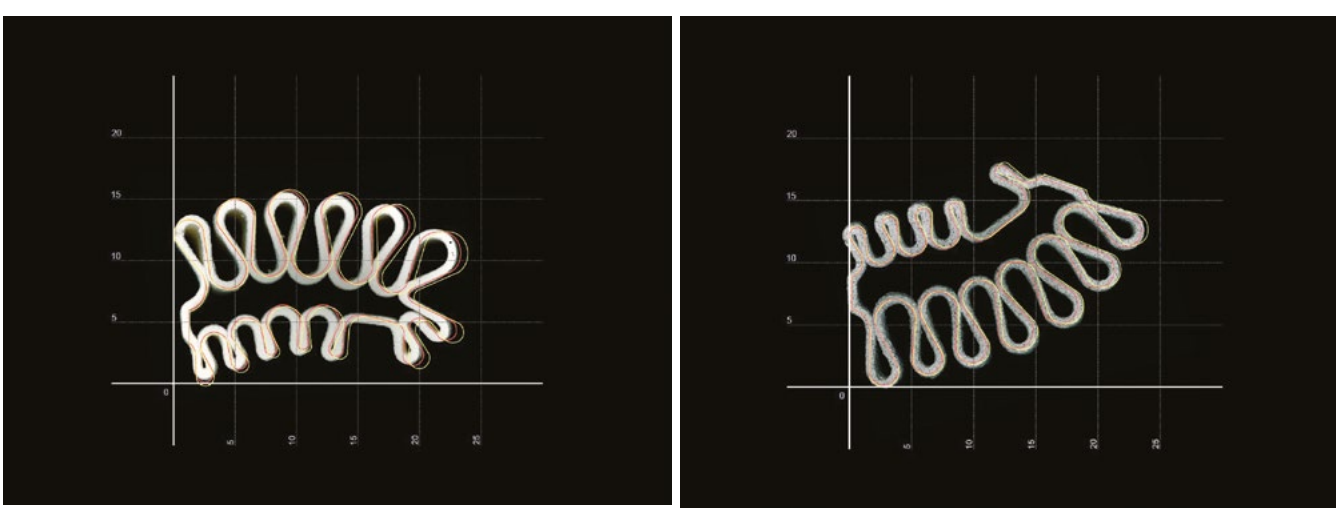

Figure 7: Shrinkage of Pulpbaffle blocks. The figure on the left shows the shrinkage of the block without a drying system and additives. The figure on the right shows the shrinkage of the block with the drying system and cork additive.

Figure 8: Final finishing of one Kusudama and Pulpbaffle block using different additives.

The additives introduced strongly influence the final color obtained. In the Kusudama blocks, it was observed that the mixture without additives produces a white finish, whereas the addition of wood powder results in a brownish tone (Figures 4-5-6-8). In contrast, the Pulpbaffle blocks acquire a greyish hue due to the color of the black cork agglomerate. Regarding the texture of the material after drying, it is determined by the presence of micronized cellulose fibers.

CONCLUSION

Through the analysis of the behavior of the mixtures under study, we concluded:

- The ideal mixture for additive manufacturing (AM) should consist of: 1 liquid material + 1 binding material + 1 fibrous material + 1 aggregate material. The binding material (starch), in conjunction with the liquid material (water), binds the fibrous particles (cellulose). The aggregate material (gelatin), when combined with the others, forms a natural adhesive, preventing the occurrence of delamination between the layers of the different blocks.
- By analyzing both mixtures, it was easy to identify that some of the defects observed in the Kusudama blocks stem from the lack of ingredients in the mixture, as well as the proportion of these ingredients.
- The greatest vulnerability observed when using natural materials lies in the drying phase, where the evaporation of water from the material causes it to shrink.
- Comparing both mixtures, it was observed that, although the height shrinkage of Mixture Kusudama is approximately 10% – less than the 19% observed in Mixture Pulpbaffle – this phenomenon is primarily attributed to delamination between layers. Although the block dimensions closely match the digital design, the wall layers tend to separate. However, delamination does not occur in Mixture Pulpbaffle, as the layers adhere to each other due to the presence of gelatin, resulting in a higher shrinkage rate. The greater the delamination between layers, the lower the shrinkage rate.
- Despite the lower shrinkage rate in Mixture Kusudama – height shrinkage of 10% – compared to Mixture Pulpbaffle – height shrinkage of 19% – greater deformations in the walls were observed, which indirectly difficult the fitting of the different modules. To ensure ease of assembly during the production of the Pulpbaffle blocks, a perforated cage was used – a system consisting of two perforated plates connected by two springs – to prevent potential deformations in the walls during the drying process.

It is essential to promote the use of sustainable, recyclable, and biodegradable materials, as the production and consumption of inorganic and non-renewable materials far exceed actual needs. The construction sector is one of the largest contributors to global pollution, making it imperative to responsibly change this scenario through the adoption of more sustainable practices, with the aim of preserving our planet. The presented case studies are clear examples of potential solutions to be adopted. Furthermore, it is crucial to implement a circular system, in which we choose eco-friendly materials that can be easily returned to the earth, fostering the growth of new species, rather than disposing of them in landfills, such as the use of cellulose and cork – natural materials. As Franklin and Till, 2018 [9] say, in a closed-loop or circular economy – the most desirable model for sustainability – materials that originate from nature are returned to nature. [10]

ACKNOWLEDGEMENTS

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3. Simulat-ing Realm

Additive Manufacturing (AM) has enticed architects and designers with promises of formal freedom and seamless digital workflows. Yet, its most significant contribution may not lie solely in formal freedom, but in enhancing the performance of built objects and enabling materials and composites that support a net-zero environmental impact. In this context, the Simulating Realm of AM emerges not merely as a validation tool but as a design enabler, a continuous partner in defining, testing, and refining AM tectonics aligned with sustainability goals such as those outlined by the Green Deal.

Simulating Realm in AM is not monolithic, it operates at least in two interlinked levels. The simulation of the material's behaviour during manufactuing, and the simulation of the built component's or building's performance after the manufactuing stage and during its use. The former is shaped by interactions such as material physical behavior, such as rheology, extrusion conditions, and process parameters, which directly influence the quality and integrity of the manufactured object. The latter is deeply influenced by design geometry, environmental conditions, and short- and long-term material performance, determining how components respond structurally and environmentally over their lifecycle. Understanding the interplay between these layers and balancing them within project-specific sustainability goals is a frontier for the success of AM in architecture.

Unlike subtractive methods where material remains inert, AM tightly couples material behavior with the fabrication process. In AM, material is alive, pushed, layered, hardened, sometimes cured or sintered, and always shaped in motion. Its behavior must be anticipated, controlled, and often adjusted in real time. Simulation is critical here, employing rheological models, toolpath simulations, thermal analysis, and printability maps to predict failures, deformations, and collapse [1, 2]. Parametric design tools like Grasshopper or bespoke optimization and manufacturing plug-ins integrate these simulations directly into the design environment, enabling adaptive control strategies that modify geometry, print speed, and layer sequencing, or even adjust material properties automatically during printing [3, 4].

This procedural intelligence, where design negotiates directly with process constraints, is well established in AM research on viscous and liquid materials such as clay, concrete [5, 6], and bio-based composites [7], as well as glass [8] and metal [9], where phase changes demand high energy input. Here, simulation does not simply optimize performance; it enables printability, ensuring that a design can be fabricated in the first place.

Each material introduces specific constraints and affordances. Simulating early shaping behavior does not guarantee control during hardening, as curing, shrinkage, cracking [10], decomposition, or biodegradation can compromise results. For instance, tools and process conditions optimized for AM of materials in a plastic state, such as clays or polymers, often become structurally inadequate or incompatible when applied materials such as rammed earth or other particulate composites, which behave differently under stress and environmental factors. What works in dry environments may deform under humidity, and mixtures stable during extrusion may lose cohesion during drying. This knowledge of material limits and potentials is essential for developing viable AM strategies. Simulation thus becomes a critical mediator between material science and architectural intent, guiding both feasibility and performance.

Artificial Intelligence and Machine Learning are extending simulation capabilities beyond traditional parametric models. By processing vast datasets that include experimental results, computer vision, sensor feedback, and environmental data, ML algorithms reveal patterns in material behavior that conventional models cannot [11, 12]. Predictive modeling anticipates shrinkage, cracking, and long-term degradation. Adaptive control systems use real-time sensor feedback to optimize deposition parameters dynamically, while generative design workflows propose geometries optimized for both printability and performance. These technologies accelerate the discovery of new, sustainable materials and act as intelligent co-pilots in the AM design and fabrication process, enhancing predictive accuracy and resilience.

Once manufactured, components enter a new performance regime: thermal, acoustic, structural, and environmental. Here, simulation shifts from process control to performance prediction. To explore how a wall panel behaves across climates, how a shading system reduces heat gain, or how material and embodied energy savings are achieved through topology optimization. These simulations connect not only to material properties but to geometry and design logic. A self-supporting vault responds to load paths shaped by printed ribs. A sound diffuser works because its material composition and form has been tuned through algorithmic simulations to address specific frequencies. Simulation embeds performance thinking early in the design phase, creating an iterative loop of simulating, adapting, printing, and validating. This loop supports and is supported by mass customization, where every component can be tailored to both formal and functional demands, making differentiation meaningful and performance-driven.

The most urgent application of simulation is in environmental sustainability. AM offers opportunities to reduce waste, use local or low-carbon materials, and develop more efficient structural systems, but these promises require simulation to become reality. By modeling embodied carbon, thermal performance, lifecycle energy use, and structural efficiency, designers make informed decisions based on data rather than intuition [13]. Simulation helps navigate trade-offs between competing priorities: a form optimized for thermal mass may use more material, while one optimized for manufacturing speed may offer lower but acceptable performance for a given context.

As architects increasingly explore natural and circular materials such as clay, recycled polymers, cellulose, and bio-based composites, simulation becomes essential to manage their variability and non-standardized properties. These materials resist generic modeling and demand sensitivity to context, moisture, composition, and process [14, 15]. Simulation bridges these gaps, allowing non-industrial materials to be used with precision and confidence.

Simulating Realm in AM is no longer a post-design validation step, it has become a design *ethos*. A design culture where performance is embedded from the start, and where material knowledge, process control, and design intent converge into systems that are both *printable* and purposeful. As the construction sector moves toward decarbonization, the Simulation Realm will be indispensable, not just for reducing waste or improving efficiency, but for redefining how we design for performance. AM gives us the tools to shape matter with precision, simulation gives us the insight to shape it responsibly. Together, they might define a tectonic logic, where buildings are not only built, but behave. In an era defined by resource scarcity and environmental urgency, this may be the relevant step that architecture can give.

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PARAMETRIC DESIGN FOR ADDITIVE MANUFACTURING: APPLICATION IN FACADE PANELS

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Manuel Jesus
Filipe Brandão
Bárbara Rangel
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The increasing emphasis on sustainability and energy efficiency in the construction sector has driven the exploration of innovative solutions to enhance building performance. This study investigates the potential of additive manufacturing (AM) in constructing thermally efficient facade panels. Drawing inspiration from biomimetic principles, the research explores how hexagonal geometries, can optimise material usage and thermal performance while maintaining structural integrity; leveraging parametric modelling tools, such as Grasshopper, the study systematically iterates through geometric configurations to balance thermal resistance, material efficiency, and aesthetic objectives. The proposed panels incorporate surface reliefs and optimised internal voids to reduce heat transfer via conduction, convection, and radiation. A computational design framework integrates thermal simulations, solar radiation analysis, and structural considerations to validate design performance. Fabrication is executed using a robotic arm equipped with an extruder, enabling precise deposition of cementitious material and demonstrating scalable manufacturing processes without traditional formwork. Key findings highlight the interplay between geometry, material distribution, and robotic manufacturing, showing that advanced designs can achieve self-shading effects, reduce thermal bridging, and improve energy efficiency. Simulation results confirm the effectiveness of surface texturing and cavity optimisation in minimising solar heat gain and enhancing insulation properties. Despite printing tolerances and prototype scaling challenges, the study validates the feasibility of creating customisable, sustainable facade solutions for diverse climatic contexts. This research underscores the transformative potential of integrating biomimetic design, parametric optimisation, and additive manufacturing to redefine energy-efficient building envelopes. It sets the groundwork for future advancements in scalable, sustainable construction practices that address contemporary environmental and performance-driven challenges.

INTRODUCTION

The architectural and construction industry is undergoing transformative change driven by sustainability and efficiency. Optimising its thermal performance is essential for buildings accounting for significant global energy consumption. Among the most promising technologies addressing these challenges is 3D Concrete Printing (3DCP), which enables the creation of customised, energy-efficient building components with minimal material waste.

This study focuses on developing thermally efficient 3D-printed facade panels, leveraging biomimetic principles and parametric modelling to optimise their design and functionality. Inspired by natural structures, such as honeycombs, that exemplify minimal material use combined with excellent structural stability, this work explores how computational design and robotic fabrication can translate these principles into functional facade elements. By tailoring panel geometries to control heat flow and reduce thermal bridging, these innovations aim to enhance energy efficiency while maintaining structural integrity.

This research explores how computational design and robotic manufacturing can be combined to refine the production of facade panels. Parametric modelling tools like Grasshopper allow for the rapid iteration of panel geometries, optimising configurations to balance thermal resistance, material usage, and aesthetic requirements. Concurrently, robotic arms equipped with 3DCP extruders facilitate the precise deposition of cementitious materials, enabling the scalable fabrication of complex forms. This integration eliminates the need for traditional formwork, reducing construction timelines and costs.

Additionally, this research employs solar radiation simulations and thermal performance analyses to validate the proposed panel designs. The study simulates real-world conditions and assesses how hexagonal surface textures, optimised cavity configurations, and self-shading mechanisms contribute to enhanced insulation and energy performance [1]. These computational insights inform the design of prototypes, which are subsequently fabricated and evaluated for their thermal and structural properties.

This study presents a novel approach to developing thermally efficient facade systems customised to diverse climatic contexts by aligning parametric design, simulation-driven optimisation, and robotic manufacturing. This work contributes to the broader adoption of sustainable practices in the built environment, addressing the need for innovative solutions in new construction.

Considering these developments, the present research focuses on thermally efficient 3D-printed facade panels. Inspired partly by biological principles where organisms evolve structures that efficiently regulate temperature [2– 5], this work explores how biomimetic design strategies can be translated into facade elements.

El-Mahdy and Ali [1] developed 3D-printed clay facade components with a self-shading texture to reduce incident solar radiation, demonstrating how surface morphology can influence thermal performance. Brian Peters' "Building Bytes" [2] explored honeycomb-like ceramic brick modules fabricated via desktop 3D printers, leveraging the same geometry honeybees use to minimize material usage while preserving structural integrity. Briels et al. [3] investigated internal cellular patterns in lightweight concrete elements, illustrating that strategically placed voids can disrupt heat flow and enhance thermal insulation. This echoes the findings of Nazzi [4], who showed how honeybee hives achieve high load-bearing capacity and thermal stability through a purely natural hexagonal arrangement. Meanwhile, in the TerraPerforma project by IAAC [5], a complex 3D-printed clay wall with biomorphic surface features was tested in real-world conditions, showing that parametric design and robotic extrusion can integrate shading and ventilation strategies within a single facade system.

Taken together, these examples underscore the potential of biomimicry for guiding the shape and internal topology of 3D-printed facade elements. Much like honeybees or other organisms that evolve structures balancing thermal regulation and structural efficiency, these precedents highlight how carefully calibrated cavities, surface textures, and geometric configurations can reduce heat transfer, mitigate solar loads, and improve insulation. By embedding such natural principles into computational design processes, the present study seeks to refine 3D-printed facade panels that draw formal inspiration from biological systems and translate those natural efficiencies into tangible thermal benefits.

Through the synergy of computational modelling and robotic manufacturing, intricate surface reliefs and internal configurations can be generated to manage heat flow, reduce thermal bridging, and potentially limit building energy demands.

A critical aspect of this endeavour is finding design methods that minimise material use while maximising insulation performance. Parametric modelling facilitates the creation of minimal contact infills, where internal cavities and supporting trusses are strategically positioned to reduce conductive pathways. Additionally, surface texturing and patterning can influence convective and radiative heat transfer, offering the opportunity to tailor facade panels to different climatic contexts.

Beyond the design considerations, practical implementation depends on effectively using 3D concrete printing (3DCP) materials. This technology enables the precise extrusion of specialized mortars or concrete mixes layer by layer, paving the way for mass customization at the building scale. 3DCP can reduce material waste and enhance sustainability in the construction process by eliminating the need for one-off formwork or costly moulds.

The primary objective of this research is to design, and prototype a 3D-printed facade panel system that offers enhanced thermal performance compared to traditional solutions. In pursuit of this overarching goal, the study is divided into two subtasks:

Geometric and textural exploration

- Developing and testing geometries and surface reliefs that improve insulation properties, attenuate heat transfer, or enable beneficial air circulation on the facade's exterior.
- Employing biomimetic principles and parametric modelling to customise patterns for various environmental conditions.

Performance-driven optimization

- Optimizing the panel geometry to balance thermal insulation, structural adequacy, and minimal material usage.
- Validating the efficacy of proposed designs through simulation and, where feasible, initial physical testing. This involves analysing internal temperature gradients, energy usage, and material consumption rates.

Ultimately, the intention is to demonstrate that parametric design and robotic fabrication (through 3DP) can enable highly efficient, customisable facade panels suitable for new construction and retrofitting. By aligning architectural ambitions with engineering analysis, this research sets the stage for broader industry adoption, encouraging sustainable construction methods that leverage the full potential of emerging technologies.

LITERATURE REVIEW

The design concept for the facade panels emerged from a synergy of biomimetic principles, aesthetic influences, and technical insights gained from prior explorations of 3D-printed building components. While the natural honeycomb motif initially drew visual interest, it was ultimately chosen for its functional performance benefits. In nature, honeycomb structures exemplify a mathematically efficient way to optimise storage space while maintaining structural stability. By distributing loads uniformly across hexagonal walls, honeycombs help minimise the total amount of material used [4]. This dual emphasis on visual order and material efficiency aligns with biomimetic design, in which geometric forms found in nature are leveraged to achieve tangible performance advantages. Indeed, previous studies of 3D-printed panels with hexagonal patterns [2,3] further support this approach, indicating how form and function can be integrated within a single geometric strategy.

Many precedents exist, such as the one by Brian Peters [2], where crafted 3D-printed ceramic bricks with hexagonal surfaces exhibit unique formal expression and functional attributes (e.g., permeability or shading). When oriented horizontally, these hexagons create an irregular yet distinctive surface; oriented vertically, their open cores facilitate air circulation and partial transparency. Nevertheless, precedents like these highlight practical challenges, particularly in establishing a continuous printing path: the extrusion path often requires duplication of specific layers. At the same time, puzzle-like interlocks can complicate toolpath planning.

These observations guided the pursuit of thermally efficient 3D-printed infill designs, as evidenced in projects such as IAAC's Terraperforma [5]. Terraperforma integrated physical tests and digital simulations to assess performance regarding solar radiation, daylighting, and structural stability. This framework gave special attention to limiting heat transfer and reducing weight, objectives that dovetail with ongoing investigations into thermal performance metrics for 3D-printed components.

Recent research underscores a series of core metrics, including U-value, thermal resistance, thermal conductivity, and hygrothermal properties, collectively defining a system's energy efficiency. The U-value measures the overall heat transfer rate through a building element, with lower values indicating more substantial insulation [6]. Thermal resistance represents the inverse of conductivity and gauges the ability of a material or wall configuration to resist heat flow. Studies by Marais et al. (2021) [7] demonstrate how reducing cavity sizes and strategically arranging them can lower U-values, as multiple air gaps impede heat flow via conduction, radiation, and convection. Hassan et al. (2024) [8] also highlight material advancements, such as refined printing technologies for managing cavity geometries to diminish thermal bridging and enhance energy regulation in building elements.

In parallel, hygrothermal properties influence the overall insulating efficiency of 3D-printed cementitious mortars. For instance, Pessoa et al. (2023) [9] characterised the thermal conductivity, specific heat capacity, dry bulk density, and water vapour permeability of a specialised mortar mix, finding that moisture content plays a pivotal role in insulation performance. Elevated water absorption leads to higher thermal conductivity and reduced efficiency, an issue that can be mitigated through advanced formulations designed to minimise moisture uptake [8].

Meanwhile, thermal conductivity (λ) is a fundamental indicator of a material's capacity to conduct heat, with lower values generally associated with superior insulation [10]. Cuevas et al. (2023) [11] explored lightweight 3D-printed wall envelopes using expanded thermoplastic microspheres (ETM), achieving notable conductivity reductions from approximately 0.74 W/(m·K) in conventional mixes to 0.45 W/(m·K) in the ETM-enhanced variant. However, balancing mechanical stability and manufacturability often requires trade-offs. For instance, while specific designs or additives (e.g., polyurethane foam infill) can significantly lower U-values, they may complicate printability, compromise structural performance, and introduce materials with less favourable end-of-life or recyclability characteristics.

Beyond straightforward cavity strategies, there is an increasing interest in complex geometries and facade designs that merge aesthetic expression with functional advantages. Leschok et al. (2023) [12] outlined a spectrum of Design-For-Additive-Manufacturing (DFAM) methodologies that employ topology optimisation, infill design, and toolpath planning to create customised facade elements. Researchers have sometimes embedded water circulation channels within 3D-printed walls, enabling active temperature control [13]. Although watertightness and printing precision can become challenging, these prototypes demonstrate the potential for multi-functional, mono-material facades incorporating insulation and heat storage in a single system.

Finally, generative design approaches facilitate multi-objective optimisation, concurrently addressing thermal efficiency, structural stability, and material consumption [7,12]. Tools like Grasshopper or Dynamo can rapidly iterate through geometric configurations by adjusting internal cavities or layer thickness to pinpoint designs that minimise heat transfer while maintaining adequate load-bearing capacity. Studies by Marais et al. (2021) [7] and Cuevas et al. (2023) [11] illustrate how systematically evaluating multiple parameters can yield various viable solutions for 3D-printed construction, each reflecting different trade-offs among insulation, durability, and feasibility [7,11].

In summary, the convergence of biomimetic geometries (e.g., hexagonal reliefs), innovative materials (foam concretes), and generative design points toward a robust framework for optimizing thermal performance in 3D-printed panels. Nevertheless, the literature highlights persistent challenges, including the need for large-scale validation, moisture control, and a balanced approach to mechanical properties. Building upon these precedents, the present work aims to refine puzzle-like interlocks, hexagonal surfaces, and parametric modelling techniques to achieve a thermally efficient, fabrication-ready facade panel prototype.

CONCEPT AND DESIGN

In the pursuit of creating a thermally efficient facade panel, two fundamental strategies were adopted:

- Surface Relief on the Panel: The first approach involves introducing relief features on the panel's surface to increase shading zones on the facade, thereby reducing direct exposure to solar radiation. Interior thermal comfort and energy efficiency can be enhanced by manipulating how sunlight strikes the panel.
- Infill Optimized for Voids, Interlocks, and Reduced Thermal Bridging: The second strategy emphasises maximising voids in the infill structure. Minimising direct contact points (thermal bridges) between the panel's layers and creating interlocks makes limiting heat transfer from the exterior to the interior possible. This improves the system's overall thermal efficiency and strengthens its insulation properties, thus supporting better energy conservation.

Hexagonal Geometry Inspiration

Nature frequently employs hexagonal patterns to maximise voids while ensuring structural resistance. Adapting this concept, a half-hexagon relief was integrated into each panel's top profile so that adjacent panels interlock and collectively form a continuous hexagonal surface (see Figure 1). Beyond achieving a formal expression, this hexagonal relief aids in shading the facade, helping maintain stable indoor temperatures and potentially reducing heating or cooling demands.

Each panel was designed to connect seamlessly with its neighbour, forming a cohesive overall surface. At the edges of the building facade, rounded panels provide a softer transition to the rest of the structure.

Puzzle-Inspired Interlocks

While the infill geometry itself did not follow a single direct inspiration, several solutions were studied, such as the one proposed by IAAC in their Terraperforma project [5]. The infill was developed to minimise contact points and, at the same time, incorporate puzzle-like interlocks (Figure 2). These puzzle joints ensure structural stability and facilitate easy panel assembly.

Parametric Schema

The parametric schema was refined to enable flexible dimension adjustments for the panel, improving design versatility and printing efficiency. This adaptability was used to fine-tune the model's specifications throughout optimisation, ensuring a more effective final print. The parametric approach facilitates customisation for different projects and performance requirements (Figure 3).

Seven parameters drive the geometry generation, three of these govern the panel dimensions (height, length, width), two parameters control interlocking features properties (interlock size, interlock gap), and the remaining are related to the printing constraints (extruder diameter).

- Height, length, width: define basic panel dimensions.
- Extruder diameter, interlock size, and interlock gap must be adjusted if the panel's width changes significantly, ensuring correct offsets and layer spacing.

To achieve a fully parametric model in future work, proportional relationships between panel dimensions and these printing parameters could be established. For instance, while the panel width is unlikely to exceed 300 mm, modifying the length should automatically adjust the interlocking geometry and its tolerances, ensuring proper fit and structural integrity.

Using the baseline rectangle, we identified critical points (mainly via the "move" command in Grasshopper) that, when connected, generate the printing path for each layer. The "hexagon depth" parameter controls the relief depth on the surface (Figure 4), but the maximum printable inclination on a vertical plane must be considered to prevent printing failures on sloped surfaces.

The side modules completing the facade are parametrically connected to the central module, which features the relief. The two side modules automatically reflect changes to the central module's design.

Therefore, the approach is organised into three main stages:

- Geometry Definition

  Each panel begins as a subdivided rectangular outline. Key points along the edges are strategically placed or shifted to form a hexagonal relief on the central panel or interlocking corners on the side panels. These points are then woven into continuous curves, which provide the basis for the final 3D shapes (Figure 4).

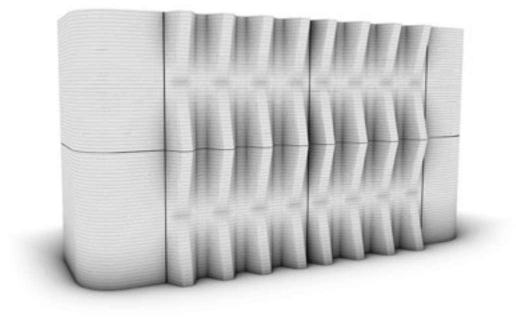


Figure 1: Representation of the connected facade panels.

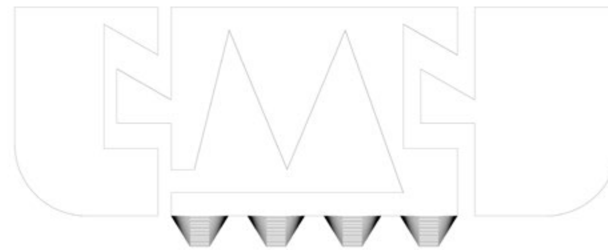
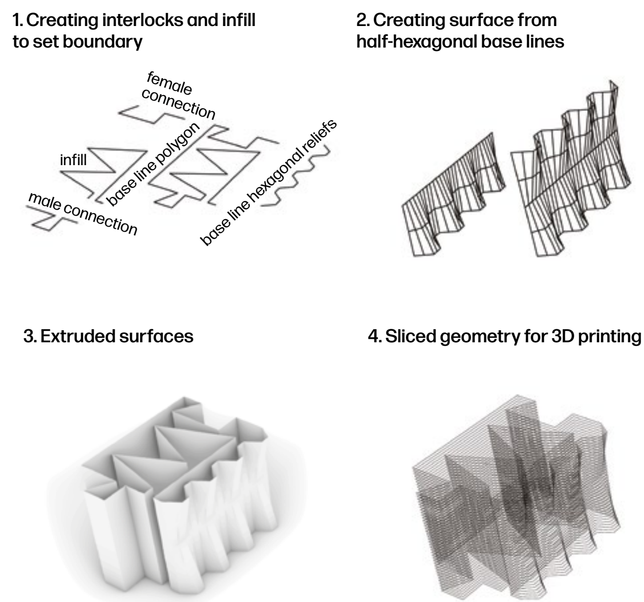


Figure 2: Plan view of the facade composition with two rounded side panels and one central relief panel.

Parameters inputs:

1. Panel height
2. Panel lenght
3. Panel width
4. Nozzle diameter
5. Hexagonal srf. depth
6. Fitting depth
7. Fitting tolerance



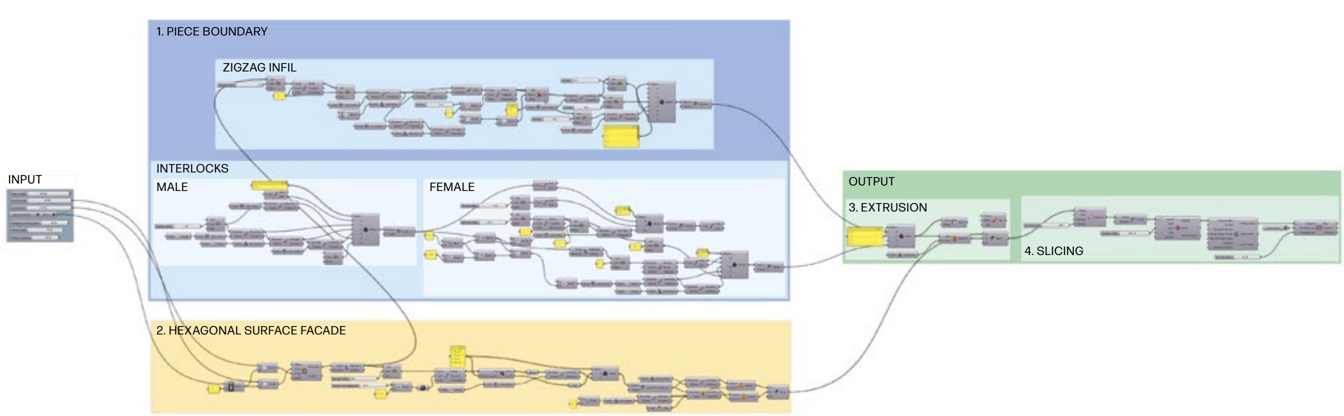


Figure 3: Parametric schema for panel generation, its printing path and overall view of the GH model.

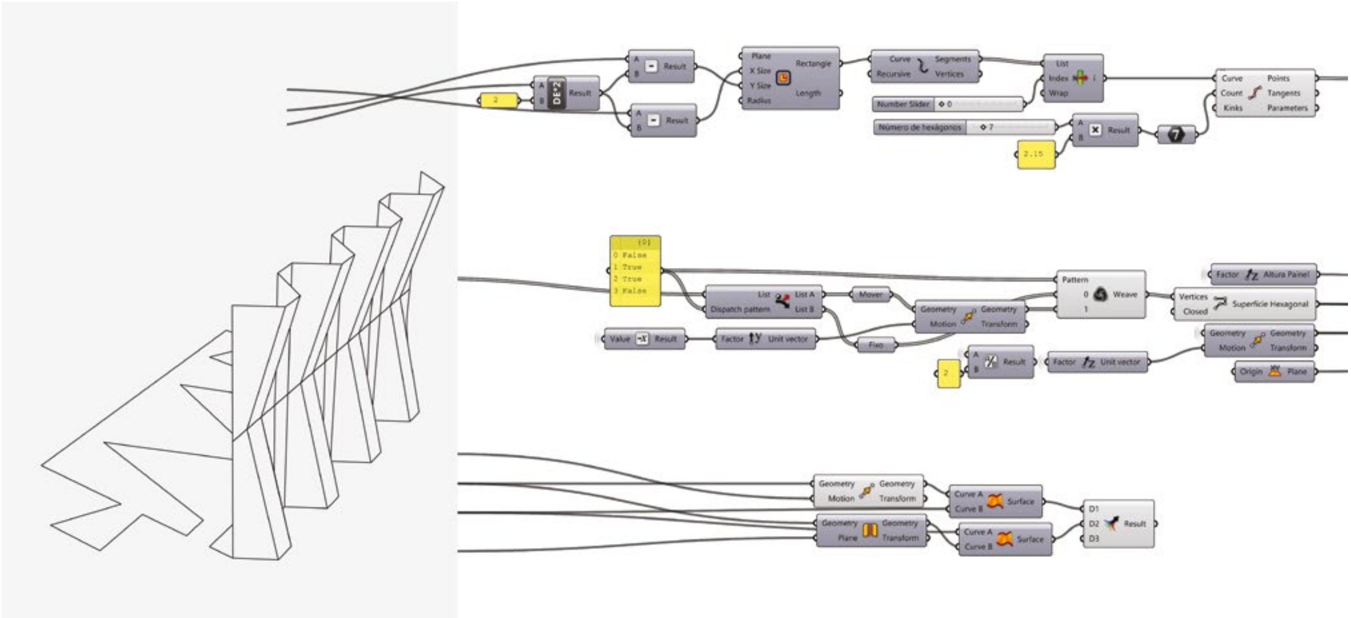


Figure 4: Model visualisation and computational model for generating the panel's relief surface.

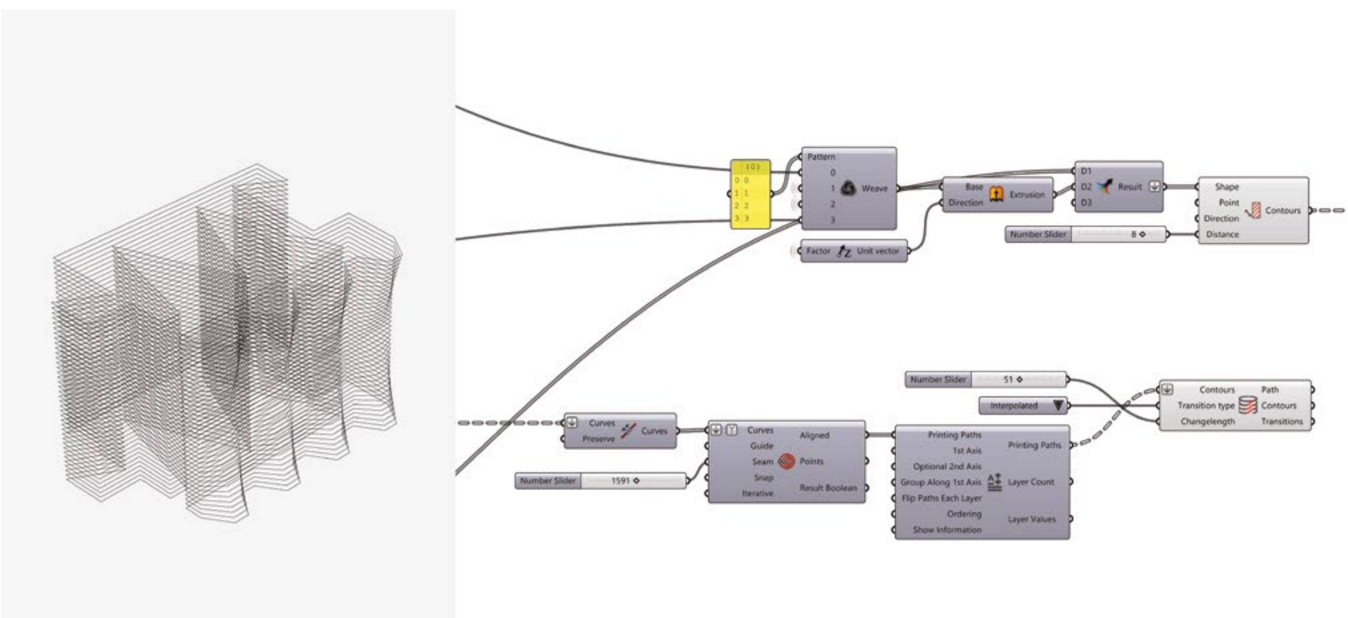


Figure 5: Model visualisation and central panel computational model of the printing path.

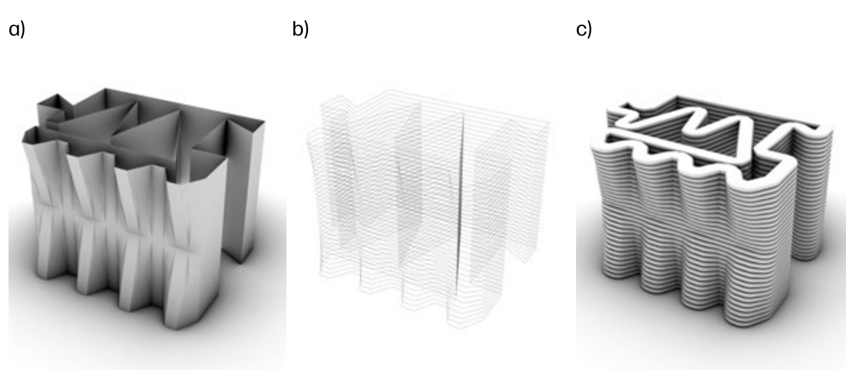


Figure 6: Digital prototypes of the central panel pieces: a) geometry, b) slicing with printing path and c) printed layers visualisation.

- Printing Path Planning
  Once the curves are generated, they are extruded to match the panel's intended thickness and height, accounting for a nozzle diameter of 15 mm (Figure 4). Spacing of approximately 30 mm reduces internal deformation and ensures consistent layer deposition. The resulting polylines define the extrusion paths in red in the Grasshopper previews to facilitate a straightforward, repeatable printing process (Figure 5).
- System Modularity
  A similar parametric logic governs the design of side panels, ensuring that relief patterns and edge profiles fit neatly with the central panel. Interlocking edges and inclined surfaces are incorporated into the same script, enabling each panel to align precisely without extensive manual adjustments.

PROTOTYPES PRODUCTION

In refining the parametric schema described above, modifications were made to inclination angles and hexagon positioning to optimise structural stability and increase solar protection. During the iterative design process, it became evident that adjusting these parameters was crucial for achieving a panel featuring prominent texture for self-shading, especially during the Spring and Summer season (April–September).

Shaded surfaces reduce direct solar exposure and alter how heat waves travel, enhancing heat absorption and dissipation and delaying penetration into interior spaces. Furthermore, when surfaces are more irregular or protruding, there is a larger surface area in contact with air, facilitating heat dissipation. These protrusions also promote convective air currents, where cooler air replaces rising warm air, lowering temperatures around the structure and improving interior thermal comfort.

These pieces were modelled in Rhinoceros 3D, and the KRL code was generated via Grasshopper (Figure 6 a)) through the curves in Figure 6 b). The 3D model of the final piece to be printed is shown in Figure 6 c).

Equipment, Materials, and Printing Parameters

A KUKA KR 120 robotic arm was coupled to an MAI MULTIMIX-3D mixer and pump. During pre-printing, the pump and hose connected to the extruder were lubricated using slurry to ensure smooth operation. For the actual printing process, the following parameters were used:

- Extruder nozzle diameter: 15 mm
- Layer width: Between 25 mm and 30 mm
- Layer height: 8 mm
- Water flow rate: 265 L/h
- Pump frequency: 15 Hz
- Robotic printing speed: 100 mm/s

Despite these adjustments, there were limitations during fabrication. When scaled down to a small prototype, the slope on the front face, meant to improve self-shading, didn't create the desired visual depth. The connections, designed as male-female interlocks between modules, also faced issues due to variations in layer width and print consistency, making the fit unreliable. As a result, the module looked blocky, and the intended thin, interlocking facade segments were not achieved.

Future designs could try L-shaped or other geometric connections to address these issues. Printing only a tiny part of the facade made it difficult to see how the modules would come together. A larger-scale print or building the complete facade would better show the self-shading effects and test how well alternative connections work. The three module types (left edge, central with relief, and right edge) are shown in Figure 7.

Lastly, the mortar showed good quality thanks to careful laboratory testing and precise water dosing during preparation. The 15 mm nozzle proved well-suited for the chosen geometry and the viscosity of the cementitious material, allowing for consistent layer deposition. Another advantage was the rapid production time, illustrating the efficiency of this fabrication method.

SIMULATION

Evaluating building components for thermal performance is critical for ensuring their efficacy in real-world applications. This study employed simulation methods to assess the thermal and solar radiation performance of the proposed 3D-printed facade panels. These simulations aim to validate the effectiveness of the geometric features, such as surface reliefs and infill configurations, in reducing heat transfer and optimising energy efficiency.

The research utilised computational tools and plugins integrated with Rhinoceros 3D and Grasshopper, specifically Ladybug, for solar radiation analysis and TRmesh for thermal evaluation. These tools were selected for their ability to model complex geometries and perform detailed environmental simulations, enabling iterative refinements to the panel designs. TRmesh is a tetrahedral meshing engine and plugin for Rhinoceros 8, developed to facilitate volumetric thermal modelling, a crucial aspect for assessing heat dissipation and energy performance in complex architectural geometries. This approach aligns with the principles outlined by Fuchs (2022) [18], which emphasises the necessity of volumetric thermal modelling over traditional methods that often rely on simplified 2D approximations, potentially sacrificing accuracy when dealing with intricate forms [18].

The simulations were conducted with two primary focuses:

- Solar Radiation Analysis: Assessing the self-shading potential and irradiance distribution on the panel surfaces to reduce solar heat gain and enhance interior comfort. This involved testing the facade design under various sun positions and climate conditions specific to Porto, Portugal.
- Thermal Performance Evaluation: Evaluating the ability of the panels to minimise thermal bridging and enhance insulation properties. This included exploring internal heat transfer through the panel's geometry and infill design.

While the solar analysis yielded valuable insights, the thermal simulation results were inconclusive due to technical challenges associated with the complexity of the 3D models. The issues primarily arose from mesh generation and geometric compatibility with the simulation software, highlighting the need for improved workflows and software adaptations.

The following sections detail these simulations' methodologies, tools, and findings, along with the limitations encountered and potential pathways for future refinement.

Solar Analysis

A digital solar radiation assessment was performed on the panel surfaces to evaluate self-shading potential and reduce solar exposure, thus enhancing interior thermal comfort. The Ladybug plug-in for Grasshopper was used to simulate microclimatic data at varying levels, following the methods of Fleckenstein et al. [14] and Maksoud et al. [15]. Although this study did not focus on external site factors or building context, these methods can be scaled up to real-world conditions.

A generic, modular deployment was chosen as the case study, illustrated in Figure 8 and Figure 9.

Historical climate data for Porto, Portugal, spanning 1980 to 2016 (Figure 10), was analysed to identify the warmest period of the year. Based on this data, the period between April 1 and September 30 was selected for the simulation. The simulation was conducted using Ladybug, a Grasshopper plug-in that imports EnergyPlus Weather Files (EPW) and allows users to perform a range of environmental simulations and analyses. Specifically, Ladybug's tools enabled the selection of the analysis period and visualisation of weather data, making it ideal for supporting decisions during early design stages.

In this study, the EPW weather file for Porto was transformed into a WEA object using Ladybug's tools, allowing for the selection of a specific time range corresponding to the warmest months. While the simulation focused on average temperatures (18°C to 24°C), the analysis did not include factors like wind, pressure, and humidity, which also influence thermal comfort.

The building was oriented along a North-South axis, and a parametric schema for solar analysis was set up to perform the solar analysis. This method requires several input parameters, including weather files and analysis periods.

Direct sun hours (Figure 12) were also examined to assess daylight exposure and its impact on thermal comfort and solar energy potential. The heat-map visualisation, along with the Grasshopper script, shows that over the tested period some areas (specially on the roof) receive considerably more sunlight. For Porto, the simulation showed a peak of 343 hours of direct sunlight during the analysis period, highlighting opportunities for natural lighting and solar energy use, while also emphasizing the need for effective shading to prevent overheating. Comparing these results with historical averages is important for adapting the design to the local climate.

Ladybug's solar radiation simulation was used to show how the facade's textured surfaces receive and distribute solar energy over time. The solar radiation simulation on the textured facade revealed that applying surface relief can significantly reduce direct exposure in critical areas. The simulation results, although combining total solar radiation without differentiating between direct and diffuse components, provide a clear overview of how the textured facade modulates irradiance across the envelope.

Specifically, when texture is applied to the facade, incident solar radiation ranges from 0 kWh/m² in well-shaded areas to approximately 652.58 kWh/m² on the most exposed southern facade. In addition, cumulative direct sun hours may go to almost 300 hours over the analysis period.

These findings underscore the effectiveness of facade texturing as a solar management strategy, improving interior thermal comfort and offering valuable insights for optimizing solar energy usage in the design process.

Thermal Analysis

A thermal analysis of the walls was deemed crucial for evaluating the facade's performance. To this end, the TRmesh plug-in for Rhinoceros 3D was initially employed to estimate the thermal behavior of the irregular solid geometries using a fuzzy-mesh approach (Figure 13). The goal was to simulate the thermal exchange across the faade panels and identify design implications for improved performance.

During this process, some software limitations were encountered regarding mesh generation and the selection of internal versus external faces for TRfem analysis in Grasshopper. In response, alternative approaches were tested, such as simplifying the original geometry and adjusting TRmesh parameters (e.g., resolution) to better suit the analysis. As a workaround, the simplified panel geometry was then exported to Therm for thermal simulation. However, because Therm tends to favour 2D, orthogonal layouts, the resulting simulation yielded only a rough estimation of the thermal behaviour.

At this stage, the thermal analysis provides preliminary insights into how the textured facade may perform, which is an important aspect to be investigated more in-depth in the near future. These early findings highlight the need for further

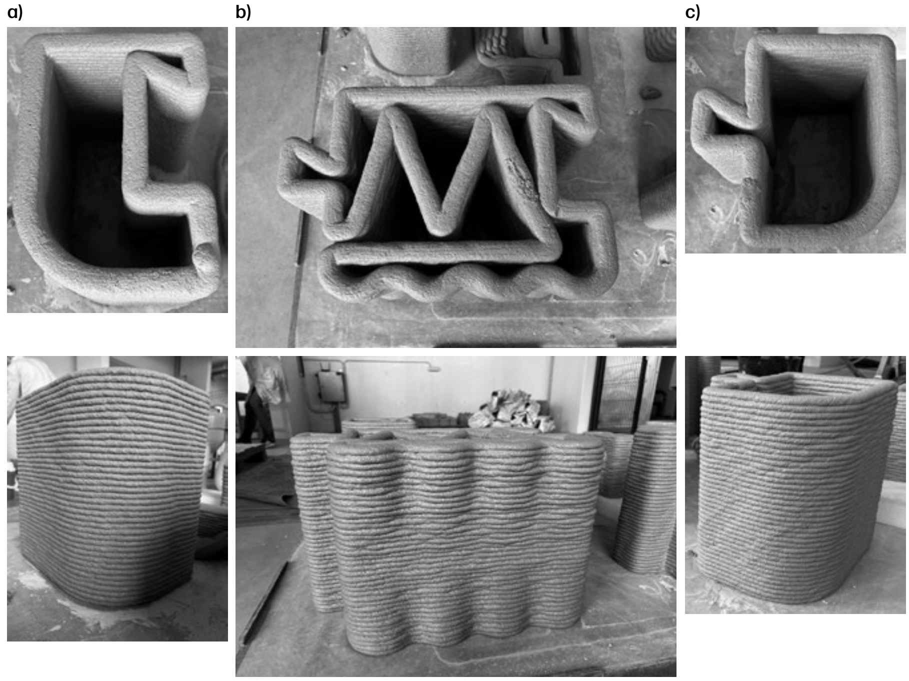


Figure 7: Panels printed with Weber 160-1 mortar: a) and c) corner panels; b) central panel.

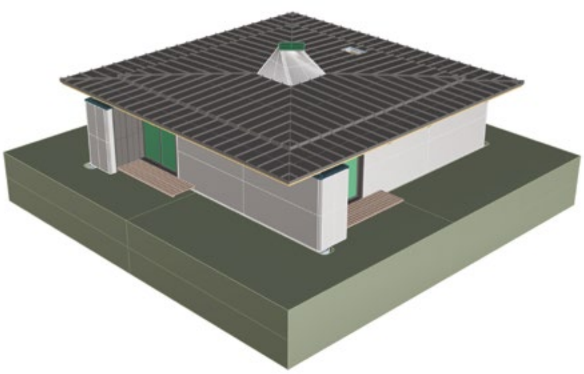


Figure 8: A base design for the case study. Font: Havelar [15].

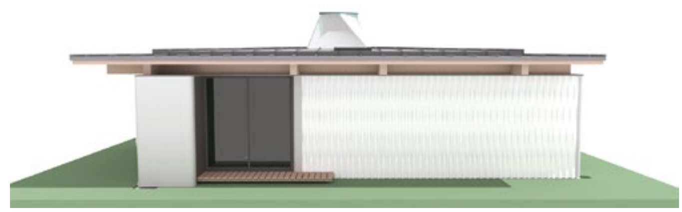


Figure 9: Final panel prototype applied to the case study.

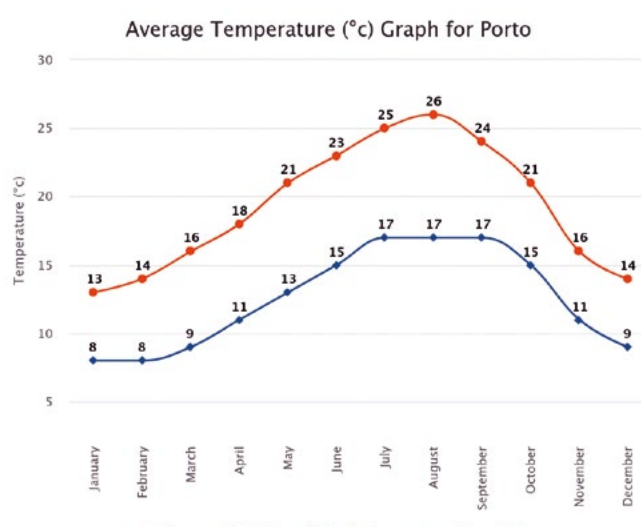
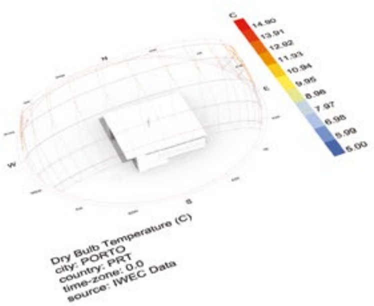
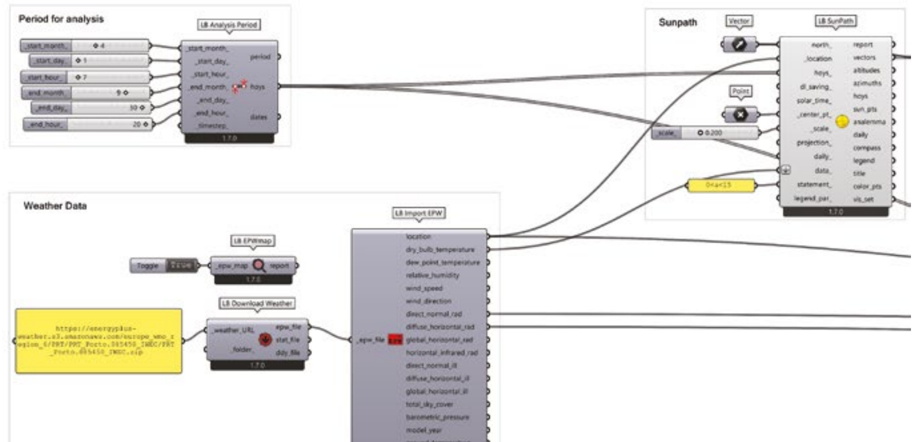


Figure 10: Average annual maximum (red) and minimum (blue) temperatures for Porto, Portugal [18].

Model visualisation



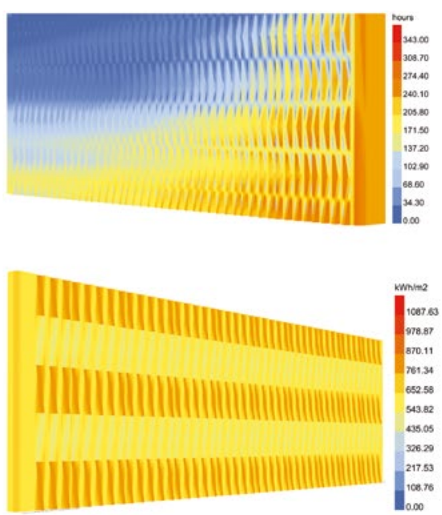
Grasshopper script



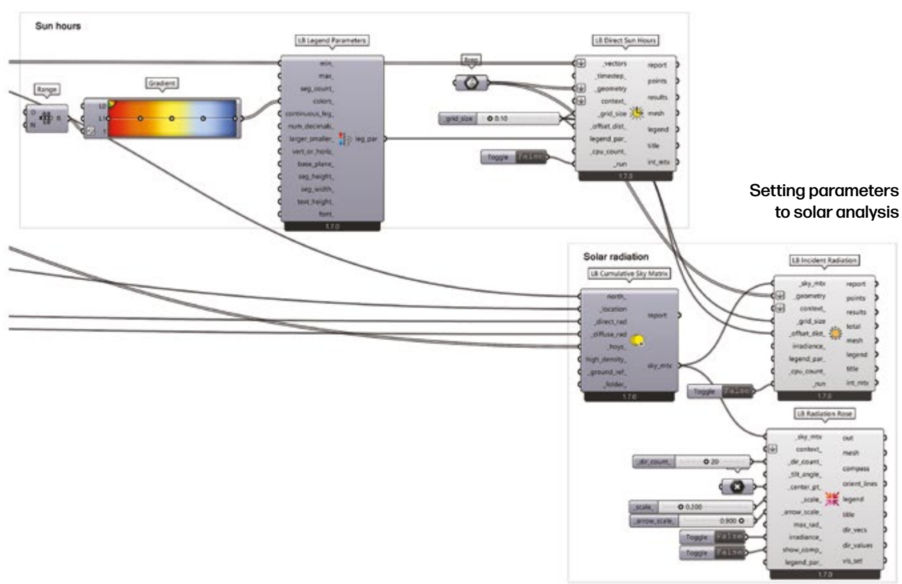
Setting parameters to sunpath generation

Figure 11: Graphical output and Grasshoper script of ladybug's simulation of the solar path between April 1 and September 30, from 07:00 to 20:00.

Model visualisation



Grasshopper script



Setting parameters to solar analysis

Setting parameters to radiation analysis

Figure 12: Graphical output and grasshopper script of direct sun hours analysis and radiation simulation.

a) b) c)

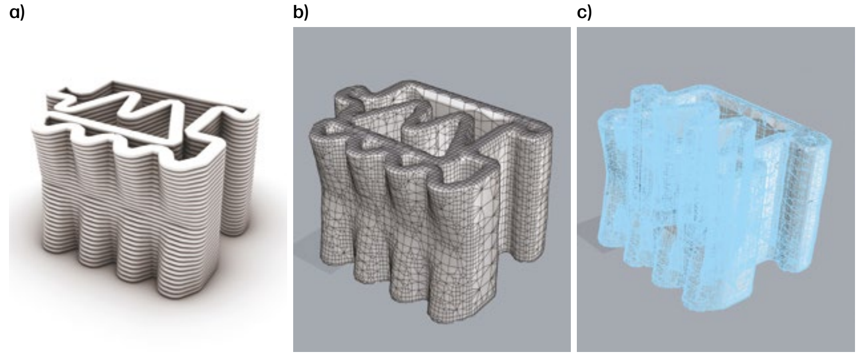


Figure 13: Initial thermal simulation of the wall using the TRmesh plug-in in Rhinoceros 3D: a) original solid geometry, b) simplified polygonal surface, c) mesh generation.

refinement of the computational workflow and the exploration of more robust simulation tools to fully capture the complex thermal interactions of the facade design.

Although a detailed thermal analysis proved challenging, this work underscores the attempt to explore innovative and sustainable solutions in construction. Further development of reliable meshing methods for complex geometries remains a key area for future research.

FINAL REMARKS

This study explored the potential of AM and parametric design to create thermally efficient facade panels. Drawing on biomimetic principles and leveraging computational tools, the development and fabrication of prototype panels featuring hexagonal surface reliefs and optimised infill geometries was proposed. While these approaches showcased promising opportunities for customisation and sustainability, several challenges and areas for improvement were identified.

Thermal simulations were conducted to evaluate the performance of the proposed designs, and the results provided a preliminary estimation of thermal behaviour. However, due to the complex geometry of the panels, the current 3D modelling and meshing workflow (using the TRmesh plug-in) produced only a rough approximation of the thermal performance. These limitations highlight the need for further refinement of the computational pipeline to enable a more detailed and accurate thermal analysis, which will be an important focus for future research.

Despite these challenges, important insights were gained regarding the panel's design and fabrication. While structurally robust, the current zigzag-shaped infill pattern has numerous material contact points, facilitating thermal bridging and potentially undermining insulation performance. To address this, future iterations should explore alternative infill geometries with minimal contact areas or incorporate insulating materials, such as cork granulates, within the voids to enhance thermal resistance. Additionally, improving the design of the male-female interlocks is essential to ensure proper fit and structural cohesion during assembly.

The study also highlighted limitations in the self-shading effect of the hexagonal surface reliefs, particularly at small scales. Larger-scale prototypes or full-scale facade systems should be fabricated and tested to assess their shading and thermal performance under realistic environmental conditions.

Future work suggestions include:

- Resolve simulation challenges:
  Improve 3D modelling and meshing workflows to enable detailed thermal analysis.
  Validate the impact of reliefs and infill geometry on heat transfer through computational and experimental methods.
- Optimise infill design:
  Test alternative infill patterns with fewer thermal bridges.
- Enhance fabrication precision:
  Refine robotic extrusion paths to improve interlock tolerances and panel fit.
  Explore new nozzle designs or printing parameters to enhance dimensional accuracy.
- Scale-up testing:
  Develop larger-scale prototypes or complete facade assemblies to assess thermal and structural performance *in situ*.
  Conduct environmental simulations with real-world climatic data to validate proposed self-shading and insulation strategies.
- Explore advanced materials:
  Investigate cement-based mortars with improved thermal performance, such as lightweight aggregates or microsphere additives.

In conclusion, while this research demonstrates the potential of AM and parametric design in creating energy-efficient building envelopes, it also underscores the importance of iterative refinement and validation. Future efforts can build on this foundation by addressing the identified challenges and exploring new design strategies to develop scalable, sustainable, high-performance facade systems for diverse architectural contexts.

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ACOUSTIC APPLICATIONS FOR ADDITIVE MANUFACTURING IN CONSTRUCTION - A REVIEW ON PROCESSES, MATERIALS, DIGITAL METHODS AND FUTURE POTENTIAL IN ROOM ACOUSTICS

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This study reviews the state of the art in room acoustics, focusing on current practices and the potential of digital technologies to enhance the implementation of acoustic measures in building projects. It briefly summarizes acoustic basics and existing regulations and examines commonly used materials, digital manufacturing and design processes for acoustically effective geometries. In particular, the study explores the opportunities provided by performance-based design and additive manufacturing to expand the applications of acoustics in construction. Despite widespread knowledge of the negative effects of poor acoustics on well-being, productivity, and health, room acoustics remain underprioritized compared to building acoustics in teaching and standardization and consequently the realization of projects. Current solutions, while effective, are limited in design flexibility. The review identifies three key parameters for efficient acoustic design: performance-based design (I), materials (II), and digital fabrication (III). Additive manufacturing, in particular, is promising for enhancing both design freedom and customization, enabling tailored acoustic panels that meet specific project requirements. Clay and paper are identified as highly suitable materials for these applications, combining sustainability with acoustic effectiveness. This research highlights the significant potential of integrating digital fabrication and advanced manufacturing techniques in room acoustics to promote healthier and more adaptable built environments.

INTRODUCTION

Performance-based design (PBD) integrates analytical and generative methods to optimize acoustics through iterative feedback loops [1]. Unlike traditional design approaches, PBD prioritizes functionality, based on predefined acoustic parameters. Efficiency improves with numerical simulations and AI-driven methods.

Conventional materials may limit customization in geometry, performance, and aesthetics. Digital fabrication, however, promises a precise structural and volumetric design, creating engineered materials with enhanced acoustic properties [2]. Advances in additive and subtractive manufacturing have expanded research in acoustic materials, moving beyond monolithic materials toward optimized, application-specific solutions.

This paper explores how digital technologies may improve room acoustics by tailoring material geometries based on space usage. It reviews recent developments in engineered acoustic materials, focusing on three key areas: acoustics, additive manufacturing, and materials in building acoustics. The study considers works published between 2010 and 2024, coinciding with the rise of digital fabrication following the expiration of the Fused Deposition Modeling patent in 2009 [3].

Relevant articles were identified through searches for the keywords *acoustics, additive manufacturing, noise reduction, sound absorption, and 3D-printed materials in* *construction*. The primary focus is interior spaces, but also studies on outdoor soundscapes are included. Only English- and German-language papers with full online access were considered.

ARCHITECTURAL ACOUSTICS

Physical basics

Sound waves are produced by longitudinal pressure differences by a moving source and characterized by the waves' speed, frequency, phase and amplitude as well as the wavelength, which is central to how sound interacts with objects [4].

If a sound wave with power P_i as shown in Figure 1 hits a surface relatively big compared to its wavelength then it is divided into parts that are reflected/ diffracted/ scattered (P_r), transmitted (P_t), passed through the material (P_f) or absorbed (P_a) [5]:

(1)
$$P_i = P_r + P_t + P_f + P_a$$

All of these sound paths can be used to work on speech intelligibility, enhancing the perception of music or suppressing noise. The science of achieving good sound within the built environment is called architectural acoustics, a subfield of acoustical engineering. Acoustics in architecture is further differentiated in inter-space noise control (building acoustics) and interior or exterior space acoustics (room acoustics) (see Figure 2). While the first finds measures to shield a room from noise transmission from another space, room acoustics is the science of sound propagation within spaces focusing on absorption and reflexion to achieve favorable sound environments for the intended use of a room.

Building acoustics primarily address sound transmission between rooms and are common in everyday projects, whereas room acoustics focus on optimizing reverberation and clarity within a space but are rarely regulated [6]. Room design must balance absorption, diffusion, and reflection to prevent adverse acoustic conditions. Room acoustics significantly impact clarity in venues such as concert halls and parliaments but are often overlooked in everyday buildings negatively effecting sound in offices, schools, or urban areas. Here, insufficient absorption exacerbates unwanted effects like the *Lombard effect*, where increasing background noise forces speakers to raise their voices, further deteriorating intelligibility. The reverberation distance r_H, which defines the point where direct and diffuse sound levels equalize, depends on absorption area and sound source distribution. Positioning speakers near reflective surfaces or employing directional loudspeakers can enhance intelligibility, but in multi-speaker environments, low-frequency buildup masks critical speech frequencies. Mitigating this requires deep-frequency absorbers down to at least 63 Hz, preferably 50 Hz, particularly in smaller rooms [5]. In environments with weakly absorbing surfaces ($\alpha < 0.2$), excessive reflections degrade sound localization, music clarity, and speech intelligibility, affecting musicians, sound engineers, and office workers. Even minor reflective surfaces can distort measurements, requiring targeted absorption when structural modifications are impractical (Fuchs, 2017).

Acoustically effective materials with sound-scattering or absorbing properties are common in construction to enhance interior acoustics. Customizing acoustic measures for specific projects is vital for efficiency but faces design and manufacturing challenges.

Acoustic Standards

Sound and acoustic design significantly influence room atmosphere, affecting perception, health, and well-being [7]. To ensure accountability and standardization, guidelines such as ISO standards, the International Building Code (IBC), the National Building Code of Canada (NBC), and the Eurocode (EC) provide regulations. In Germany, state-level regulations specify acoustic requirements, as summarized in Figure 3.

German building codes mandate minimum sound insulation based on usage, primarily outlined in DIN 4109 and DIN 12354. Stricter requirements, such as VDI 4100, may be applied upon request. While inter-room noise control is regulated, room acoustics—sound performance within a single space—lack mandatory codes. Instead, planners rely on general recommendations, including ISO 23591 for music venues and workplace guidelines such as VDI 2569 ("Office Acoustics"), DIN 18041 ("Room Acoustics"), and ASR A3.7 ("Noise"). DIN 18041 is particularly relevant for optimizing room acoustics.

Due to their non-mandatory status, these standards are rarely implemented, leading to a focus on sound insulation over intelligibility. As a result, classrooms, offices, and conference rooms often suffer from poor acoustic conditions, causing high sound pressure levels and communication difficulties (Nocke, 2019).

PERFORMANCE-BASED DESIGN

Nature exemplifies advanced acoustic optimization, as seen in moth wings that disrupt bat echolocation through sound absorption, echo reflection, and frequency alteration, effectively camouflaging them from predators [9]. These bioinspired principles offer new possibilities in acoustical engineering, achieving effects unattainable with conventional surfaces [10] and show the portential of precise adaptation to specific conditions in order to achieve effective sound control. Sullivan's principle of "Form Follows Function" (1896)

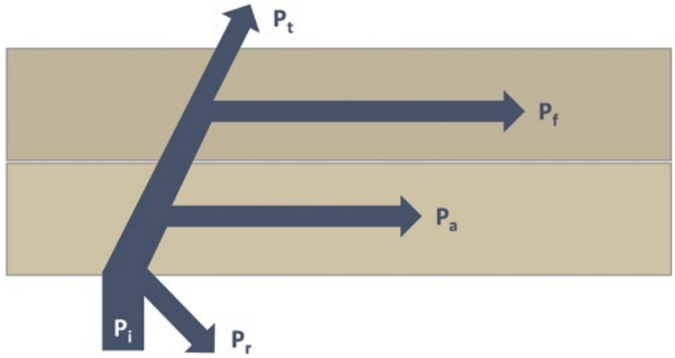

Figure 1: Interaction of sound and materials: possible sound paths.

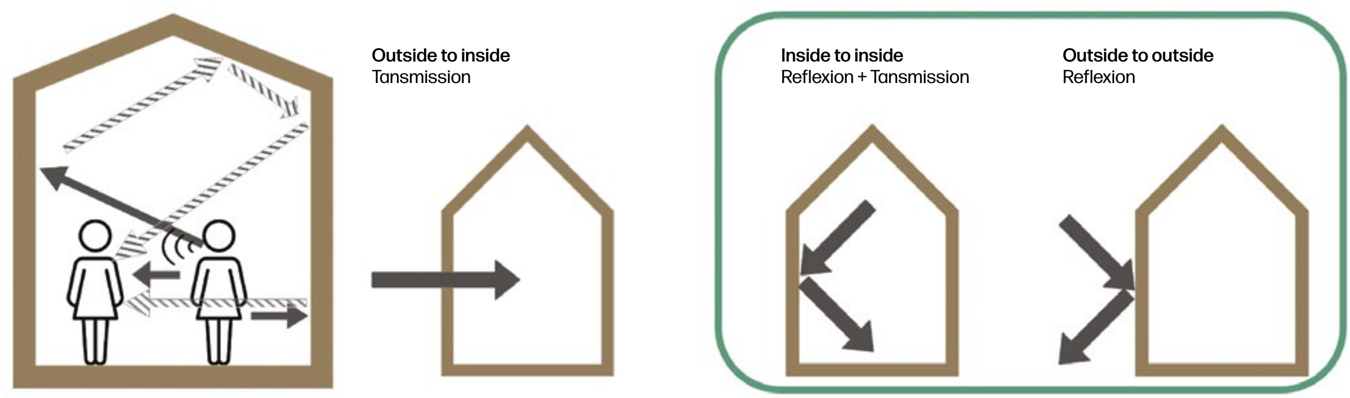

Figure 2: inter-space, interior and exterior acoustics (left) and retroreflections within a space (right).

Calculation of reverberation time	Requirements for rooms
DIN EN ISO 12354-6 Absorption/Reverberation Time: 2004-04	DIN 18041 Audibility: 2016-03
	ASR 3.7 Noise: 2018-05
	VDI2569: 2019-10

Evaluation materials	Experimental standards
DIN EN ISO 11654 – Absorption Coefficient: 1997-07	DIN EN ISO 3382-1 Performance Spaces: 2009-10
ISO20189 – Soundabsorption: 2018:11	DIN EN ISO 3382-2 Ordinary Spaces: 2008-09
	DIN EN ISO 3382-2 Open Plan Offices: 2012-05
	DIN EN ISO 354 Lab. Sound Absorption: 2003-12

Table 1: Overview of German codes for interior space acoustics (reproduced and modified from [8])

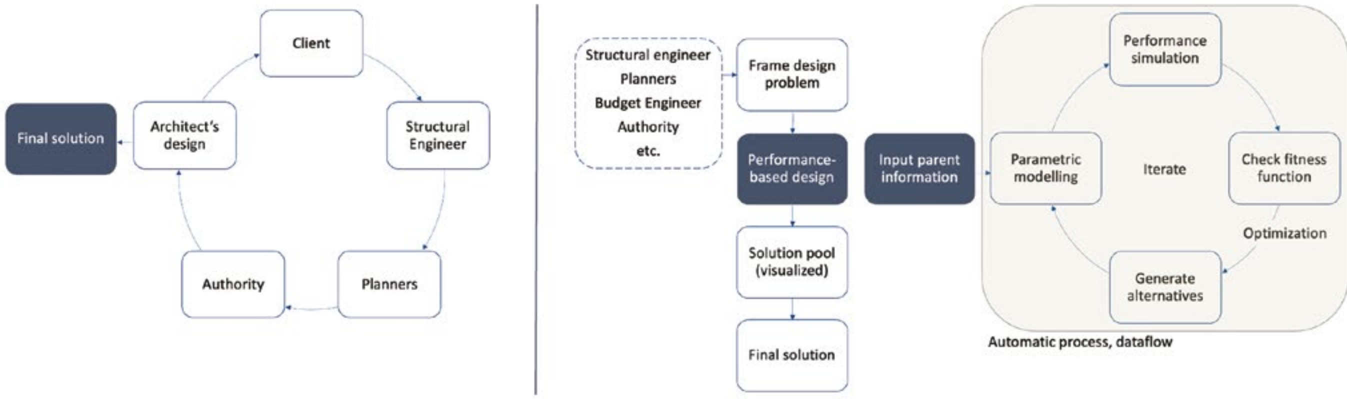

Table 2: Sound absorption coefficients of different common building materials [reproduced and modified from [41],[42]].

Material	Description	125 Hz	250 Hz	500 Hz	1kHz	2 kHz	4 kHz	Mean value
Clay	rammed earth (100 mm)	0,15	0,22	0,27	0,29	0,34	0,48	0,29
	rammed earth (100 mm) with clay plaster (7 mm)	0,05	0,05	0,09	0,09	0,09	0,14	0,09
Ceramic	brickwork, 10 mm flush pointing	0,08	0,09	0,12	0,16	0,22	0,24	0,15
	standard brickwork	0,05	0,04	0,02	0,04	0,05	0,05	0,04
	smooth brickwork, flush pointing	0,02	0,03	0,03	0,04	0,05	0,07	0,04
	ceramic tiles, smooth surface	0,01	0,01	0,01	0,02	0,02	0,02	0,02
Concrete	porous concrete blocks	0,05	0,05	0,05	0,08	0,14	0,2	0,10
	rough concrete	0,02	0,03	0,03	0,03	0,04	0,07	0,04
	smooth concrete, unpainted	0,01	0,01	0,02	0,02	0,02	0,05	0,02
	smooth concrete, painted	0,01	0,01	0,01	0,02	0,02	0,02	0,02
Plaster	gypsum plaster tiles, 17% perforated, 22 mm (ceiling)	0,45	0,7	0,8	0,8	0,65	0,45	0,64
	plasterboard on frame, 100 mm airspace	0,3	0,12	0,08	0,06	0,06	0,05	0,11
	plasterboard on cellular core partition	0,15	0	0,07	0	0,04	0,05	
								0,00
Wood	plywood, mounted solidly	0,05		0,05		0,05	0,05	0,03
	plywood, 12 mm, over 50 mm airgap	0,25	0,05	0,04	0,03	0,03	0,02	0,07
	plywood, hardwood panels, over 25 mm airspace, solid backing	0,3	0,2	0,15	0,1	0,1	0,05	0,15
Paper	sprayed cellulose fiber (16 mm on solid backing)	0,05	0,16	0,44	0,79	0,9	0,91	0,54
	sprayed cellulose fiber (75 mm on solid backing)	0,7	0,95	1	0,85	0,85	0,9	0,88
Glass	glass, 4 mm	0,3	0,2	0,1	0,07	0,05	0,02	0,12
	glass, 6 mm	0,1	0,06	0,04	0,03	0,02	0,02	0,05
	glass 2-3 mm, double glazing, 10 mm air gap	0,15	0,05	0,03	0,03	0,02	0,02	0,05
Metal	steel decking (floor)	0,13	0,09	0,08	0,09	0,11	0,11	0,10
	metal, 32% perforated, backed by 30 mm rockwool (ceiling)	0,12	0,45	0,87	0,98	1	1	0,74
	person, adult, standing	0,15	0,38	0,42	0,43	0,45	0,45	0,38
Other, in m^2 units	plastic chair, hard seat	0,07	0	0,14	0	0,14	0,14	0,08
	chair, cloth upholstery	0,44	0,6	0,77	0,89	0,82	0,7	0,70

Figure 4: Design workflow: traditional (left), performance-based design (right) [reproduced and modified from [12]].

highlights the importance of purpose-driven design in architecture. While not a new concept, advancements in digital modeling and manufacturing now enhance these aspirations. Despite the persistence of formalistic design trends, functional optimization tools are increasingly shaping architectural solutions [11].

Traditional design workflows remain time-consuming and imprecise, relying on iterative adjustments based on individual preferences. Performance-based design (PBD) similarly considers boundary conditions and desired characteristics but differs by automating output generation through logic-based modeling rather than direct design modeling [12]. As shown in Figure 4, the generated solutions are then evaluated by the project team to determine the optimal outcome.

Advances in digital modeling and manufacturing enable greater design complexity, facilitating new theoretical concepts and experimental validation [13]. With increasingly complex building requirements, performance-based design plays a central role.

Parametric software allows visualization of intricate geometries, enabling function-oriented material design across scales, known as architectural infrastructure materials. This approach adapts geometry to environmental conditions, space usage, and room shape while enabling rapid production of customized components. It is widely used in auditorium design to enhance acoustics for musicians and improve speech intelligibility [14–16]. The Smithsonian Museum's courtyard roof exemplifies how multiple factors—structural integrity, shading, and sound absorption—can be integrated [17].

Technological advances, particularly numerical simulations and parametric design, streamline feedback between generation, evaluation, and modification, making applications more accessible to planners [18]. Parametric modeling tools like Grasshopper for Rhinoceros support acoustic performance evaluation based on material and geometric properties, using programs such as Odeon [19], CATT-Acoustics [20], Treble [21], and Pachyderm Acoustics [22] . Pachyderm integrates design and analysis within Grasshopper, improving coordination [23]. Recent projects favor integrated design environments, reducing interoperability risks between visualization and simulation tools [12].

Grasshopper modules like the solvers Galapagos [24, 25] and Octopus [20] optimize predefined parameters, allowing automated incorporation of simulation results and algorithmic refinement for greater precision. [26] combined noise analysis, parametric design, and simulation to integrate acoustic benefits into landscape design. The study demonstrated potential noise reduction strategies for Munich Airport.

Metamaterials are high-performance structures with properties beyond natural materials, composed of periodic meta-atoms. Digital manufacturing advancements have led to their increased development. Metamaterials are classified into fields like nanophysics [27, 28], mechanical [29, 30], elastic [31, 32], and acoustic [33, 34]. Current construction research focuses on mechanical metamaterials [35] like auxetics to reduce earthquake damage [36] and composites for structural reinforcement [37]. Acoustic metamaterials manipulate sound waves through periodic meta-atoms, useful for noise reduction by redirecting sound via reflecting meta-surfaces [38, 39] propose acoustic metasurfaces with C-shaped meta-atoms for sound reflection adjustment whereas [40] suggest H-shaped meta-atoms. Both achieve a wide-angle sound reflection of up to 80°. Acoustic properties depend on material, geometry, and arrangement, suitable for noise control in urban areas, facades, and sound barriers at various sites.

MATERIAL CONSIDERATIONS

Common building materials include clay, ceramics, wood, concrete, steel, and glass. Especially in the field of architectural acoustics paper and gypsum need to be mentioned additionally. Depending on characteristics like its density a material's capacity for sound absorption varies (see Figure 5) making some a better option for certain applications than others.

While clay, plaster, and paper have rather positive sound absorption properties, dense materials like ceramics, metal or glass are for the most part reflective. The latter therefore need to be combined with high absorbent materials or can be used in room acoustics to transport sound. The material groups will subsequently be shortly reviewed in terms of their typical use and acoustic performance regarding their capacity for sound absorption. Furthermore, their use for AM in the built environment shall be briefly outlined.

Ceramics and Clay

Clay, one of the oldest building materials, still remains prevalent in construction due to its global availability [43]. It can be distinguished between dried (clay) and fired (ceramics) products.

Fired elements are classified as ceramics, typically composed of clay, loess, and clay marl [44]. Industrial processes allow for varying properties, including porosity, which influences sound absorption. While ceramics generally exhibit high reflectance, increased porosity enhances absorption. Particularly additives like charcoal, which burn during firing leave pores and thereby improve performance at higher frequencies [45, 46]. For applications requiring maximal reflection, surface roughness can be adjusted through glazing, engobing, or modifying porosity via sintering at higher kiln temperatures [44].

Dried elements are typically referred to as clay or loam. Loam, a mix of clay, sand, and silt, is traditionally used in rammed earth, clay bricks, and panels for non-load-bearing walls [47]. Unlike ceramics, unfired clay has a higher sound absorption coefficient, further enhanced by fiber additives. Rammed earth surfaces achieve frequency- and humidity-dependent absorption coefficients up to 0.58, significantly outperforming concrete and lime-cement plaster across a broader frequency range [41, 42]. Its sustainability, high thermal mass and hygric behavior are furtherly demonstrating the material's suitability for indoor applications.

In research in the built environment different technologies are already well established for the additive manufacturing with clay. While robotically rammed earth [48] produces sturdy structures, only simple large-scale structures are possible to realize, similar to automated sprayed earth, where the wet mixture is applied with high air pressure with a drone [49, 50]. On the contrary the base material for binder jetting is dry earth powder which is locally solidified a fluid ecological binder [51]. While it enables the fabrication of parts with larger bridges and overhangs, the production is rather time-consuming and has disadvantages regarding the process stability. Extrusion offers a compromise between printing speed and producing high-resolution objects that gain their stability not through their mass, but through internal stiffening.

Additive manufacturing techniques for shaping can be easily integrated into the process chain of structural ceramics [52]. In addition to the original Cartesian extrusion systems, systems with extended motion control, have increased the design possibilities for integrating additional functionalities through further degrees of freedom [53]. While additive manufacturing with loam can be used to print whole buildings [54], additively manufactured ceramic parts are usually limited in size by the kiln and include smaller scales. This aspect seems to make AM ceramic parts only suitable for a complementary use in the built environment, for example when it comes to restauration [87]. Nevertheless, when integrated into industrial processes larger pieces and numbers can easily be fired thereby also making it a good use case for CCA where bricks are additively arranged into structures [79].

Paper and Wood

Paper is an established acoustic absorber due to its low density and environmental benefits. Commercial products exist for sound insulation [55], while ongoing research explores room acoustical applications. Panels made from recycled egg trays and natural fibers (corn husk, sugar cane) highlight the potential of sustainable solutions [56]. Another approach optimizes cellulose-based multilayer composites for sound absorption [57].

Wood, though less absorbent, is commonly used in resonators. Hybrid materials, such as cork-wood combinations, have demonstrated superior absorption in impedance tube experiments, offering sustainable alternatives [58].

A number of researchers have already made use of the potential of those sustainable materials in additive manufacturing. The technology already found its way into the construction sector: Commercially available products are birdhouses or insect homes for biodiversity in green facades [59].

The base material for 3D paper printing usually consists of cellulose, carboxymethylcellulose, lecithin and a filler such as chalk or starch [60, 86]. Aside from the challenges in regards to humidity or shrinkage its characteristics make it a good fit for acoustic applications [60]. Just like paper also research on wood AM mainly focuses on extrusion with a similar mixture consisting of wood particles and a starch binder. A challenge for these materials is the slow drying and therefore low green strength and the forming of mold [61].

Concrete and Plaster

Common concrete consists of cement, water, and aggregates, including sand and gravel. Admixtures are often added to enhance workability, durability, or setting time. For acoustic applications, specialized concrete is used to reduce sound transmission. Lightweight aggregates like expanded clay or pumice create a more porous structure, improving sound absorption.

Plaster and gypsum-based materials are also widely used for walls, ceilings, and soundproofing. For the latter especially perforated ceiling tiles [62] are widely used, but also perforated wall elements or fiberboards are common. Gypsum is the primary ingredient, combined with water and additives like retarders, fibers, or perlite to improve strength and acoustic properties. Some products include mineral wool or foam fillers to enhance sound absorption.

While various materials have been explored in the past years, concrete remains the dominant choice for additive manufacturing [63]. Research in the field is steadily progressing and depending on the usage different suitable technologies are available. Concrete offers the advantage on effortlessly realizing prints on a large scale which means it is applicable to print houses in-situ or realize pre-fabricated parts. With a modular gantry printer even two story-buildings can be realized relatively fast using contour crafting, an extrusion process [64]. Shotcrete printing also offers the possibility of realizing large objects fast. The procedure applies concrete by compressed air with the compromise of a relatively lower resolution [49]. On the other hand, approaches like injection printing [65] so far are limited to smaller dimensions but come with the opportunity of working with an enlarged freedom of design because of the support that the surrounding gel offers distancing the technology from the common planar layers in additive manufacturing. Gypsum on the other hand is difficult to use in extrusion processes due to its long setting time. Though approaches tried to develop adjusted mixtures [66] additive manufacturing with gypsum mixtures is barely implemented.

Glass

The most prevalent glass types in the built environement are soda-lims slicate glass and borosilicate glass. Due to its closed surface and high-density glass of course has a very low sound absorption coefficient below 0.1 and is not common for acoustic measures. At the same time its importance in construction and high percentage in facades give it an extraordinarily high potential to improve room acoustics, especially outdoors in urban areas [67]. By carefully engineering the geometry of a glass façade the design can help diffusely scatter or relocate sound to reduce the sound pressure level in certain areas.

Because of its characteristics glass 3D-printing comes with a lot of challenges. As a material it has high strengths but is also brittle and needs high temperatures during processing. Nevertheless, in the past few years different reliable technologies have been developed that are able to meet the demands of the construction sector. For the common applications with soda-lime silicate glass Fused Deposition Modeling (FDM) has proven to be a good choice [68]. Another printing technology in the field that is being investigated is Direct Energy Deposition (DED) [69]. When it comes to facades, additive manufacturing is of use especially when it comes to shaping or modifying the flat planes and rethinking the way we work with them. Promising concepts include AM supports [88] in order to reduce the visuak imapact of joints, AM sealings of insulated glass units (IGU), stiffening of glass façades by adding AM ribs or simply aesthetic design applications within a building [89].

Steel

An even metal plane is highly reflective with sound absorption values of up to 0.1. Adjustments in the geometry like perforations and angles or the combination with absorbing materials significantly improved the acoustic performance of metal facades [70].

Regarding steel various applications for the built environment are possible from a high output to (in-situ) manufacture bridges [71, 72] to manufacturing fairly smooth surfaces. The majority of projects in the field of additive manufacturing with steel focus on the production of entirely printed elements like freeform columns [73] or nodes produced with Wire Arc Additive Manufacturing (WAAM) [74]. Since in facades freeform is becoming a key subject in recent projects involve the additive manufacturing of individualized nodes out of steel with smaller tolerances Directed Energy Deposition Laser Wire (DED-L)) [75] and the forming and stiffening of freeform steel sheet panels. The welded reinforcement not only helps in shaping and stiffening the sheets but also reduces production costs and saves material [76].

The variety in studies and research projects highlight the growing interest in additive manufacturing for the built environment and emphasize the need for further functional applications. Therefore, research in material optimization and process development is necessary, as well as sustainable solutions to address current limitations and expand commercial applications.

DIGITAL FABRICATION FOR ACOUSTIC APPLICATIONS

Digital manufacturing technologies are rapidly evolving across various fields, with additive manufacturing (AM) gaining prominence in construction due to its design flexibility and potential for complex (acoustic) applications. However, AM in architecture faces two key challenges: (1) large-scale geometries and (2) high material demands, including weather resistance, load-bearing capacity, and durability [77]. A wide range of AM technologies and materials are available, selected based on desired properties and functionality [78]. Research spans lab-scale experiments to full-scale demonstrators, with Robocasting favored for its high-speed production, meeting industry demands [79].

Digital technologies are transforming acoustic optimization in building design. Using computational design, simulation tools, and digital fabrication, architects and engineers create efficient and sustainable solutions. The focus is on controlling sound through scattering, absorption, and resonators to manage reflections and reverberation. Unlike traditional methods, digital fabrication allows for complex, custom acoustic elements, enhancing performance and aesthetics. The following section outlines Computerized Numerical Control (CNC) technologies relevant to acoustics and construction, emphasizing material feasibility and application scope.

Subtractive Technologies

Subtractive methods take away material to reach the final form, hence they are more similar to common conventional technologies than additive manufacturing. By combining digital design with robotics or CNC-milling complex structures can be derived.

An integral approach by Rossi et al. [16, 80] combines material, production method, form, acoustics and visual effect and examines their interdependencies. used brick elements for the acoustic modular design of interior spaces. They used robotic subtractive production using oscillating wire cutting produced clay blanks with complex individual geometries. In addition to their ability to micro-regulate sound through their porous texture, digital manufacturing technologies expand the possibilities of ceramic elements on a macro scale through function-based design [16, 80]. Giglio et al.[14] developed a workflow for the design of customized acoustic interior surfaces based on computational design and manufacturing processes (CNC milling). The aim was to combine optimized reflection, scattering and absorption properties in the final product.

Additive Technologies

Products that make use of diffuse scattering particularly benefit from the individualized mass production that digital methods offer due to the easy adaption of the dimensions of the reflecting structure related to the considered frequencies and the room's requirements [81].

Absorber systems effectively utilize digital technologies to reduce sound levels through passive destructive interference at specific frequencies [82]. Material and surface roughness significantly impact performance, with smoother surfaces enhancing effectiveness. Attempts to incorporate diffuse scattering by bending geometries were negligible in acoustic benefit and caused temperature stress buckling [83].

AM acoustic panels can further be improved by using natural fiber-reinforced polymer composites in FDM to enhance mechanical as well as acoustical properties [84].

Measures for the outside of a facade using digital technologies on the other hand are rare. A pre-study at TU Darmstadt included the development of an additively manufactured acoustically effective ceramic façade [85].

The idea behind the functionality of the design is visualized in Figure 6. The parabolically shaped elements direct sound waves into their interior. Thereby, the sound waves are deflected upwards. The upper parts of the system are designed with an infill structure to further scatter and absorb sound. Size, curvature and opening can be varied depending on the orientation of the sound source and the most dominant frequency range. Compared to the reference object with an even surface, a SPL reduction of up to 7 dB was demonstrated for the tested facades.

CONCLUSIONS

Additive Manufacturing (AM) offers significant advantages in acoustic material production, enabling precise control over design and fabrication. While clay may not match the acoustic performance of specialized foams, its excellent hygric properties and sustainability make it a viable alternative compared to other common materials in construction like concrete, glass, or metal. AM allows for the optimization of porosity and frequency response in clay-based acoustic elements, addressing limitations of conventional manufacturing. However, process-related variations, such as porosity inconsistencies and surface roughness, must be carefully managed to ensure reproducible mechanical properties.

Despite growing interest in clay 3D printing and its ecological benefits, current processes are constrained by coarse resolution and material variability. To facilitate its adoption in acoustic applications, further research is needed to refine material formulations, optimize process parameters, and establish reliable drying methods. Prefabrication of such components requires a systematic approach to ensure dimensional accuracy and structural integrity. Additionally, hybrid strategies—such as applying 3D-printed textures onto prefabricated panels—could enhance acoustic performance while enabling scalable production.

Digital fabrication presents new possibilities for performance-driven acoustic solutions, yet its application to natural materials like clay remains underexplored. Integrating computational design with AM can lead to tailored acoustic elements that improve interior soundscapes while maintaining environmental efficiency. Future research needs to focus on refining printing techniques, developing hybrid solutions, and deepening the understanding of material-process interactions to enable the reliable, scalable production of clay-based acoustic systems.

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Figure 5: Additively manufactured acoustically effective ceramic facade [85].

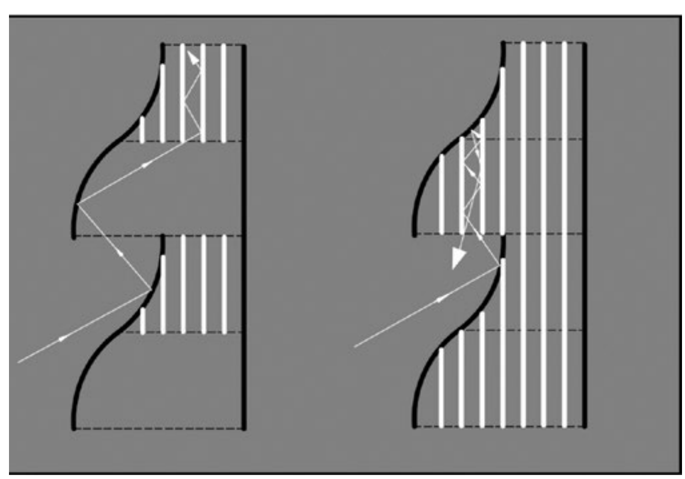

Figure 6: Soundpaths within the printed facade elements [85].

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MULTI-SCALE HYBRID TOPOLOGY OPTIMISATION: FOR ADDITIVE MANUFACTURING SHELL ENVELOPES USING ADVANCED ALGORITHMS

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Paulo Mendonça
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The synthesis of shell shapes for robotic Additive Manufacturing (AM) with earth-based composites is crucial due to rapid hardware advancements, increased AM accessibility, and the drive for sustainable construction. Shell structures, known for their material efficiency, design flexibility, and load-bearing capabilities, often face deformation and failure during construction, especially when using earthen and cement-based materials. The traditional masonry shells capitalize on compression strengths, AM introduces challenges such as increased tensile stresses, bending moments, and the necessity for supports in cantilevered sections. Addressing these issues is key to advancing sustainable shell envelope construction through robotic AM. Advances in computational framework methods are introduced, enabling the design and mass customization of shell envelopes to explore various design scenarios suitable for construction AM, focusing on self-supporting surfaces that utilize ribbed systems to enhance structural efficiency. The development of *HybridOpt*, a C# based Grasshopper plugin, is presented as a tool to establish a seamless connection between Grasshopper and SAP2000v24 via its Open Application Programming Interface (OAPI) in C# for a comprehensive analysis of shell maximum stresses and strain. The computational framework integrates the Bidirectional Evolutionary Structural Optimization (BESO) method to enable mass customization of ribs while leveraging finite element analysis (FEA) software. Additionally, Karamba3D, a Grasshopper plugin, performs principal stress analysis within the shell envelope, enhancing structural performance evaluation and optimization of the shell mass and strain energy. Furthermore, the acquired technique explores the effects of topology optimization strategy on the structural performance of AM shell envelopes, offering a comprehensive computational framework for the future construction of AM applications.

INTRODUCTION

Topology optimization

Topology optimization has emerged as a pivotal tool in engineering design, offering a systematic approach to achieving optimized structural layouts within specified design domains, guided by particular objectives and constraints. This methodology is especially valuable in industrial applications due to its minimal requirement for prior design knowledge, making it accessible and efficient for a wide range of applications. The foundational work by Bendsøe and Kikuchi (1988) introduced homogenization-based topology optimization, which has since become the basis of the field. Despite its potential, the single-scale reconstruction of homogenized results presents challenges, particularly in approximating the conformality and periodicity of multi-scale structures on a finite length scale [1].

Topology optimization is a computational technique that optimizes material distribution within a design domain to enhance structural performance under given constraints. It systematically removes low-stressed material while ensuring minimal variations in the stiffness matrix throughout subsequent optimization steps[1].

The goal is to find the structural layout that best transfers specific loading conditions to supports, thereby generating an acceptable initial layout of the structural system, which can then be refined through shape optimization procedures.

In the context of structural engineering, topology optimization can be employed to assist designers in defining a structural system that best satisfies operating conditions.

The integration of topology optimization into commercial software, such as SAP2000V24, is facilitated through the use of an open application programming interface (API)[1,2].

Shell Structures for AM

Shell structure optimization in structural engineering demonstrates superior efficiency, providing an optimal balance between mass minimization and mechanical strength. This characteristic renders shell structures particularly advantageous for A dditive M anufacturing (AM) applications.

The utilization of shell geometries, as opposed to solid counterparts, yields significant benefits in terms of material economy and fabrication speed, thereby reducing overall production costs.

In cases where shell morphologies are dictated by factors beyond external load distributions, structural enhancement is often necessary. This is typically achieved through localized reinforcement strategies, such as:

- Selective thickness augmentation in critical regions
- Integration of ribbed support structures

These methods aim to improve the load-bearing capacity and overall structural integrity of the shell without compromising its inherent lightweight properties. The optimization of such reinforcement strategies remains an active area of research in computational design for AM, focusing on the balance between material usage and mechanical performance [3].

Ribbed-shell structures

These structures are designed to enhance the mechanical performance of shell structures by adding ribs along principal stress lines.

The ribs are closely attached to the shell, which helps in utilizing the bending characteristics and avoiding stress concentration, thus providing better stability compared to other supporting structures like pillars or frames.

The ribbed-shell structures are advantageous because they do not occupy much internal space and can have variable cross-sectional shapes to meet different performance goals [3].

Shell stresses

Principal Stresses: are the components of a stress tensor when the basis is changed such that the shear stress components become zero. The stress tensor has three real eigenvalues and three mutually orthogonal eigenvectors, which are used to determine the principal stress directions. These directions indicate trajectories of internal forces and naturally encode the optimal topology for any structure under given boundary conditions.

Von Mises stress is widely used to predict the yielding of materials under any loading condition. It is a scalar derived from the Cauchy stress tensor and is used in the system to ensure that the material does not exceed its yield strength. The von Mises stress is calculated using the formula that involves the orthogonal normal stresses and orthogonal shear stresses.

Stress computation and optimization: the process of setting up the static equilibrium equation of rib-reinforced shells to calculate nodal displacements using the Finite Element Method FEM. This involves re-meshing the surface so that all ribs lie on the edges of the resultant triangular mesh, and modeling each rib as beam elements. The contribution of the ribs to the shell is obtained by superimposing the element stiffness matrix of the ribs onto the shell's stiffness matrix. The optimization aims to minimize material usage while achieving the required structural stiffness [3].

Problem formulation

Achieving optimal mass distribution and structural stability in shell envelopes fabricated through robotic Additive Manufacturing (AM) with earth-based composites presents a critical challenge.

Due to the material's low tensile strength and vulnerability to deformation, shell structures must be designed to minimize bending moments and tensile stresses while ensuring load-bearing capacity.

Traditional approaches rely on experience-based heuristics to define the thickness and reinforcement of shell structures, often leading to inefficient material use or inadequate structural performance.

To address these limitations, the Bidirectional Evolutionary Structural Optimization (BESO) method is employed to systematically optimize the mass distribution of the shell envelope, ensuring that material is concentrated in regions that contribute most to load-bearing efficiency while reducing unnecessary mass.

The BESO method, integrated within the AMEBA topology optimization plugin, is used to define the structural optimization and computational framework.

Within this framework, load types (such as self-weight, live loads, and wind pressure), principal stresses simulations, are systematically applied to the shell, while

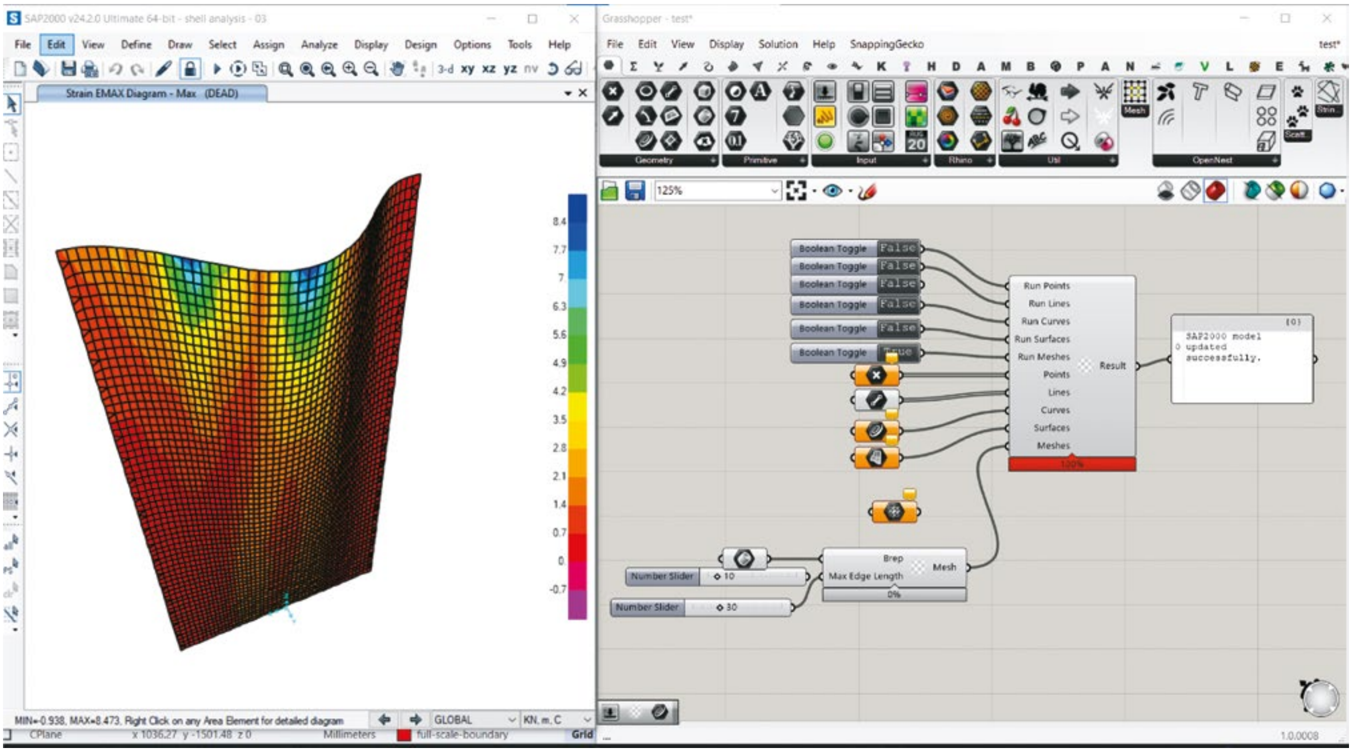

Figure 1: Developed the *HybridOpt* Grasshopper plugin to establish a seamless link between Grasshopper and SAP2000v24, while also implementing an advanced computational framework for stress analysis.

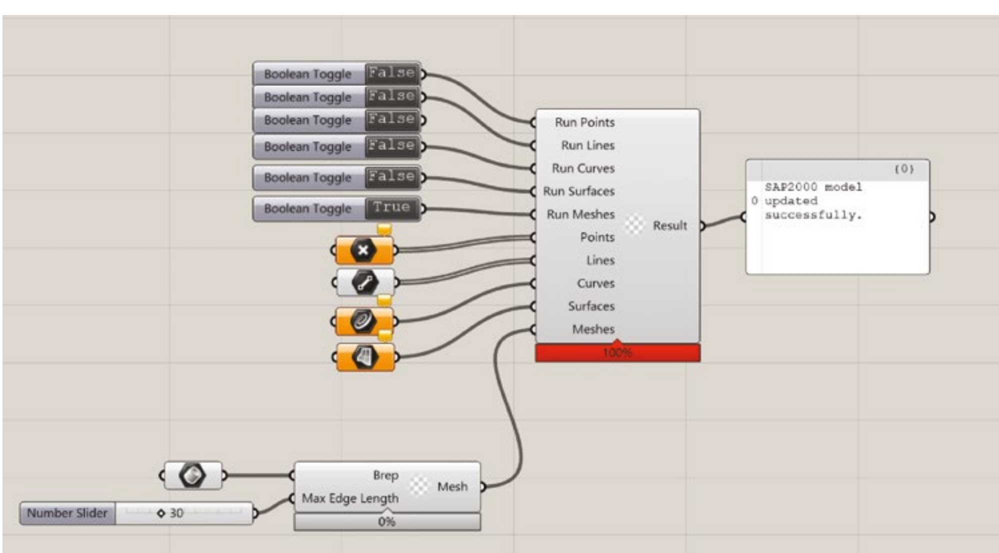

Figure 2: Developed a C# component for generating a mesh subdivision and Livelink suite in (SAP2000v24).

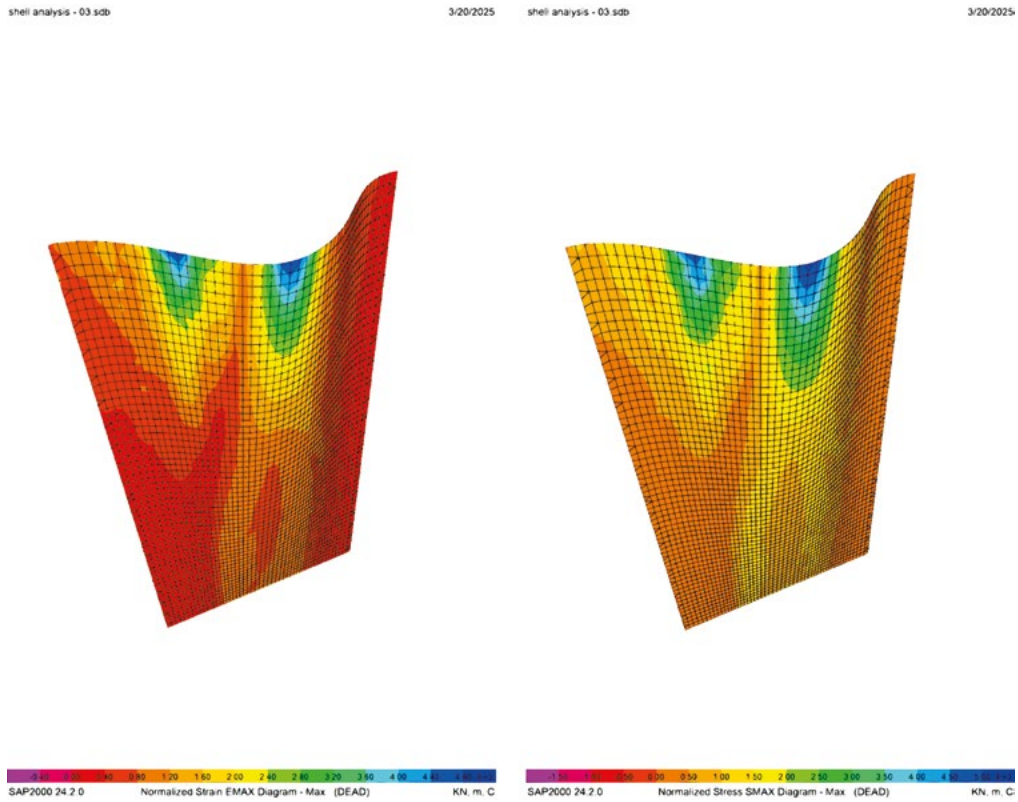

Figure 3: The normal stress and strain principal direction in 3D, indicating the tensile and compressive stress along shell envelop, SAP2000v24.

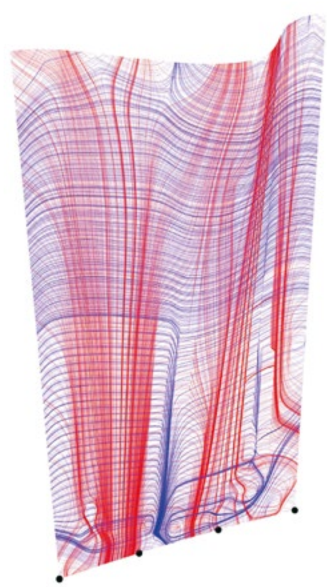

Figure 4: Principal moment lines in a vertical shell element under load, showing how bending forces flow to the supports at the base (red indicating the major principal moments, blue the minor).

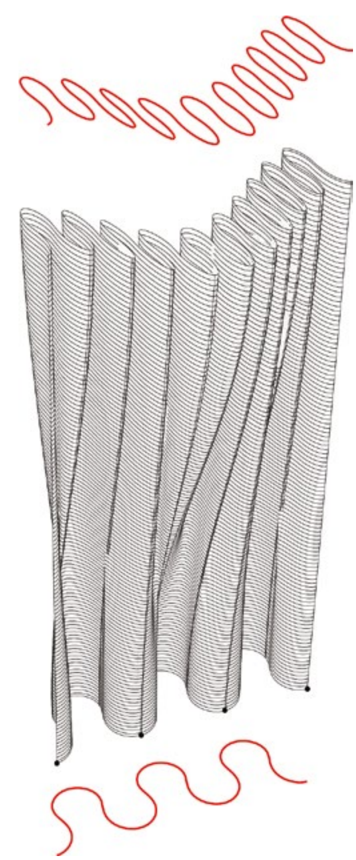

Figure 5: The shell geometry's ribs are aligned with the maximum stress directions to optimally distribute mass and enhance structural efficiency.

anchor points are strategically positioned at critical support or ribs locations to enhance stability in the construction AM process.

The design domain is established to encompass the entire shell geometry, allowing for the gradual evolution of an optimized form that maximizes structural performance.

Additionally, boundary conditions including fixed ribs supports are carefully defined to reflect realistic constraints in construction AM scenarios.

The material properties of earth-based composites, including compressive and tensile strength, Young's modulus, and density, are incorporated into the optimization process to ensure accurate structural stress and strain simulation analysis with developed Livelink into data base software SAP2000V24 for an accurate result.

Livelink between Grasshopper and (SAP2000v24)

Developing a C# Grasshopper component that creates a live link between the geometries generated in Grasshopper and Rhinoceros 8, while the stress analysis performed in (SAP2000v24). This integration allows precise stress analysis of the shell structures, helping to identify potential failure points and optimize the design early in the process.

The *Hybridopt* C# script is a Grasshopper developed plugin component that establishes a live link with SAP2000v24 for structural analysis. It imports key libraries for handling geometry (Rhino.Geometry), Grasshopper integration (Grasshopper.Kernel), and SAP2000 API interaction (SAP2000v1). Encapsulated within the Hybridopt namespace, it extends GH_Component, inheriting Grasshopper functionalities. The component initializes two private variables, cOAPI mySapObject (SAP2000 API connection) and cSapModel mySapModel (structural model), enabling real-time export of points, lines, curves, surfaces, and meshes for SAP2000v24 simulations.

```
using System.Collections.Generic;
using Grasshopper;
using Grasshopper.Kernel;
using Rhino.Geometry;
using SAP2000v1;
namespace Hybridopt
{
public class HybridoptComponentV24 :
GH_Component
{
private cOAPI mySapObject;
using System;
private cSapModel mySapModel;
public HybridoptComponentV24()
: base("HybridoptComponentV24", "Hybrid-opt",
"Live link between Grasshopper and SAP2000",
"Category", "Subcategory")
{
}
protected override void RegisterInputParams(GH_
Component.GH_InputParamManager pManager)
{
pManager.AddBooleanParameter("Run Points",
"RP", "Run the SAP2000 script for points", GH_
ParamAccess.item);
pManager.AddBooleanParameter("Run Lines",
"RL", "Run the SAP2000 script for lines", GH_
ParamAccess.item);
pManager.AddBooleanParameter("Run Curves",
"RC", "Run the SAP2000 script for curves", GH_
ParamAccess.item);
pManager.AddBooleanParameter("Run Surfaces",
"RS", "Run the SAP2000 script for surfaces", GH_
ParamAccess.item);
pManager.AddBooleanParameter("Run Meshes",
"RM", "Run the SAP2000 script for meshes", GH_
ParamAccess.item);
pManager.AddPointParameter("Points", "P", "List of
points to export", GH_ParamAccess.list);
pManager.AddLineParameter("Lines", "L", "List of
lines to export", GH_ParamAccess.list);
pManager.AddCurveParameter("Curves", "C", "List
of curves to export", GH_ParamAccess.list);
pManager.AddSurfaceParameter("Surfaces", "S",
"List of surfaces to export", GH_ParamAccess.list);
pManager.AddMeshParameter("Meshes", "M", "List
of meshes to export", GH_ParamAccess.list);
}
protected override void RegisterOutputParams(GH_
Component.GH_OutputParamManager pManager)
{
pManager.AddTextParameter("Result", "R", "Result
of the SAP2000 script", GH_ParamAccess.item);
```

This C# script converts a Brep into a Mesh while controlling the maximum edge length of mesh faces. The Solve Instance method retrieves a Brep input and an optional edge length parameter (maxEdgeLength), defaulting to 1.0. If valid data is provided, it calls BrepToMesh(maxEdgeLength), converting the Brep into a mesh using custom BrepExtensions.

The Brep extensions class defines BrepToMeshes, which generates a mesh array using Meshing Parameters, and Join Meshes, which merges multiple meshes into a single entity. The resulting optimized mesh is then output in Grasshopper for further processing.

```
protected override void SolveInstance(IGH_
DataAccess DA)
{
```

```
Brep brep = null;
double maxEdgeLength = 1.0;
if (!DA.GetData(0, ref brep)) return;
if (!DA.GetData(1, ref maxEdgeLength)) return;
Mesh mesh = brep.BrepToMesh(maxEdgeLength);
DA.SetData(0, mesh);
}
public override Guid ComponentGuid => new Guid("1a6e45b7-6e2b-4d8c-82e9-8a3a7a6fce2d");
protected override System.Drawing.Bitmap Icon => null; // Add an icon if available
}
public static class BrepExtensions
{
public static List<Mesh> BrepToMeshes(this Brep brep, double maxEdge)
{
Mesh[] mesh;
MeshingParameters mp = new MeshingParameters
{
MaximumEdgeLength = maxEdge
};
mesh = Mesh.CreateFromBrep(brep, mp);
return mesh.ToList();
}
public static Mesh JoinMeshes(this List<Mesh> meshes)
{
var rtnmesh = new Mesh();
foreach (Mesh mesh in meshes)
{
rtnmesh.Append(mesh);
}
return rtnmesh;
}
public static Mesh BrepToMesh(this Brep brep, double maxEdge)
{
return JoinMeshes(BrepToMeshes(brep, maxEdge));
}
```

Structure Optimization Framework

Beyond mass optimization, rib topology takes a crucial role in reducing buckling effects and minimizing strain energy in the shell envelope.

By leveraging the AMEBA plugin for topology optimization, rib placement is guided by principal stress trajectories, ensuring reinforcement is provided where the shell experiences maximum compressive and tensile forces.

This strategic rib layout enhances global stiffness, reduces deformation under load, and improves the structural integrity of thin shell sections, which are highly susceptible to buckling. Furthermore, by optimizing rib topology, the framework effectively reduces strain energy concentration, leading to a more uniform stress distribution across the shell.

By integrating BESO-based mass optimization and rib topology refinement, this research provides a computational framework that enhances the efficiency and feasibility of AM-fabricated shell structures.

The proposed method not only improves structural performance but also aligns with sustainable construction principles by minimizing material waste while maximizing load-bearing efficiency. Topology Optimization of Shell envelopes: developing an algorithm using (BESO) computational framework implemented in AMEBA plugin within Grasshopper, which optimizes the material distribution in the shell envelope.

This tool is crucial for adjusting the rib mass and shell mass to improve the overall structural performance of the AM shell.

The Bidirectional Evolutionary Structural Optimization (BESO) framework provides a powerful method for optimizing material distribution within a structure by iteratively removing inefficient material while reinforcing critical load-bearing regions.

Unlike gradient-based optimization approaches, which allow for gradual material transitions, BESO employs a binary material distribution strategy, systematically converting regions into either solid or void.

This discrete adjustment ensures that only structurally essential material remains, leading to an efficient mass distribution that enhances performance while reducing material waste.

The exploration of these previous aspects serves the main purposes: minimizing strain energy and maximizing structural stiffness.

To accomplish these objectives, we present a computational framework for building an advanced Grasshopper algorithm using KARAMBA 3D and SAP2000V24 that simulates and analyzes computationally shell stress distribution lines. Our strategy focuses on strategically placing rib mass along primary stress paths, enhancing the stiffness of the shell, and optimizing its structural integrity. This tailored approach is geared toward maximizing mechanical effectiveness, particularly suited for the intricacies of construction 3d printing [2,4].

BACKGROUND

The rib-reinforced shell structures, a computational framework has been developed to enhance the structural strength and stiffness of shells by integrating ribs along principal stress lines. This approach ensures that the ribs follow paths of material continuity, which are indicative of internal force trajectories. The framework involves several stages, including the generation of a dense rib network, simplification of the network by removing non-contributory ribs, and optimization of rib flow and cross-section. The ribs are designed to swing on the surface, allowing for adjustments that improve structural performance.

The principal stress lines, which guide the rib placement, are calculated using Finite Element Analysis (FEA) on the shell structure. This analysis provides a principal stress field that is used to generate a quad-mesh, aligning the mesh edges with the stress directions5. The rib network is then extracted from this mesh, ensuring that the ribs are optimally placed to reinforce the shell. The optimization process also includes the use of hyperelliptic T-sections for the rib cross-sections, which help in reducing stress concentration and improving mechanical performance. This method has been validated through experimental results, demonstrating that rib-reinforced shell structures achieve significantly higher strength and stiffness compared to pure shells of the same material volume [3].

In recent years, construction AM, particularly with concrete and earth, has seen significant advancements, necessitating the development of new shape-design methods. Bhooshan introduced the concept of Function Representation to address the challenges of spatial coherence in print paths, which is crucial for ensuring that each layer of material has sufficient overlap with the preceding one. This approach contrasts with the traditional 'slicing' paradigm, which often lacks spatial coherence and requires significant domain expertise.AM through a combination of shape interpolation (Morph) and affine interpolation. This method reduces the expertise needed to create complex, nearly-print-ready shapes and provides visual feedback regarding the constraints of concrete and earth printing. The Morph & Slerp framework is particularly innovative as it adapts ideas from Optimal Mass Transport, a concept historically rooted in the Earthmovers problem, to ensure spatial coherence between print layers. Furthermore, the analogy of concrete or earth printing to masonry design, particularly pitched-brick vaulting, is a significant precedent for this work. The historic masonry structures, showing that they are composed of simpler geometric primitives laid along self-supporting arched courses, similar to AM along print paths. This historical context provides a foundation for understanding the potential of the proposed shape-design methods in modern 3D printing applications [4].

METHOD

This research paper employs a computational framework that combines topology optimization, finite element analysis (FEA), and principal stress evaluation to design and optimize additively manufactured AM shell envelopes.

The framework integrates the Bidirectional Evolutionary Structural Optimization (BESO) method for mass customization of ribs, ensuring that structural material is allocated efficiently in regions of high stress. In parallel, a standard FEA solver is utilized to compute principal stress distributions, displacements, and strain energy, forming the foundation for iterative design updates as shown in Figure 6 , and Figure 7.

This dual approach (topology optimization + FEA) aims to maximize structural performance while minimizing material usage, thereby reducing weight ,time and cost for large-scale AM applications.

Geometry Definition and Ribs Setup

The process begins with defining the shell envelope geometry in a parametric modeling environment. The geometry is discretized into a finite element mesh suitable for both the BESO algorithm and FEA. Key input parameters such as material properties, boundary conditions, loading scenarios, ribs topology and target volume reduction are specified to guide the optimization.

Once the mesh and constraints are established, the initial shell model is analyzed under load to determine baseline stress and displacement values.

BESO-Driven Topology Optimization

The BESO method iteratively refines the shell structure by adding or removing material in regions of low or high stress, respectively.

The algorithm identifies areas underutilized in carrying load and systematically eliminates them, while simultaneously reinforcing high-stress regions or mentioning the potential ribs regions.

This bidirectional approach preserves a continuous load path throughout the optimization process, maintaining structural integrity. At each iteration, the updated geometry is reanalyzed with FEA to capture the evolving stress distribution. Convergence is achieved when predefined criteria such as minimal strain energy, maximum stiffness, or targeted mass reduction are met as shown in the results and Figure 6 , Figure 7 , Figure 8 , and Figure 9.

Principal Stress Analysis with Karamba3D

In parallel to the BESO optimization, Karamba3D (a Grasshopper plugin for structural analysis) is employed to evaluate principal stresses within the shell as shown in Figure 4. By visualizing major and minor principal stress lines, to identify critical load paths and potential stress concentrations. These insights guide the strategic placement and orientation of ribs, ensuring they align with principal

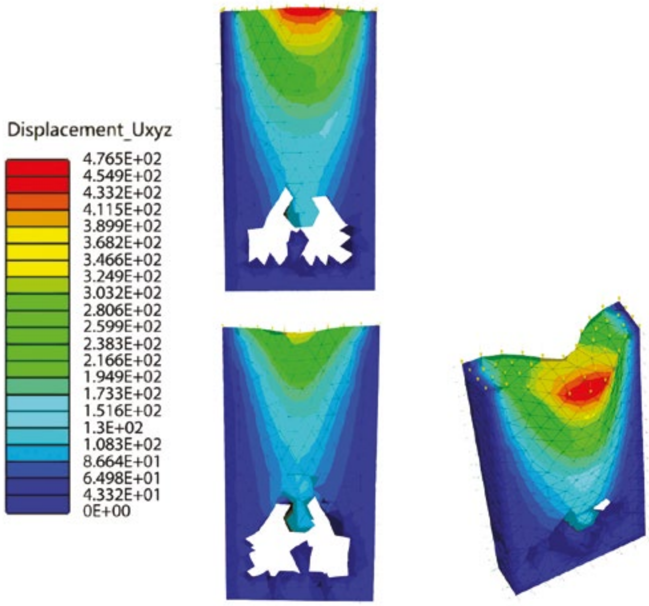

Figure 6: Displacement contours (Uxyz) for the shell envelop wall, illustrating how the structure deforms under applied load.

Figure 7: The final iteration achieves a volume fraction of approximately 0.95 while stabilizing the total strain energy near 3.74×10^6.

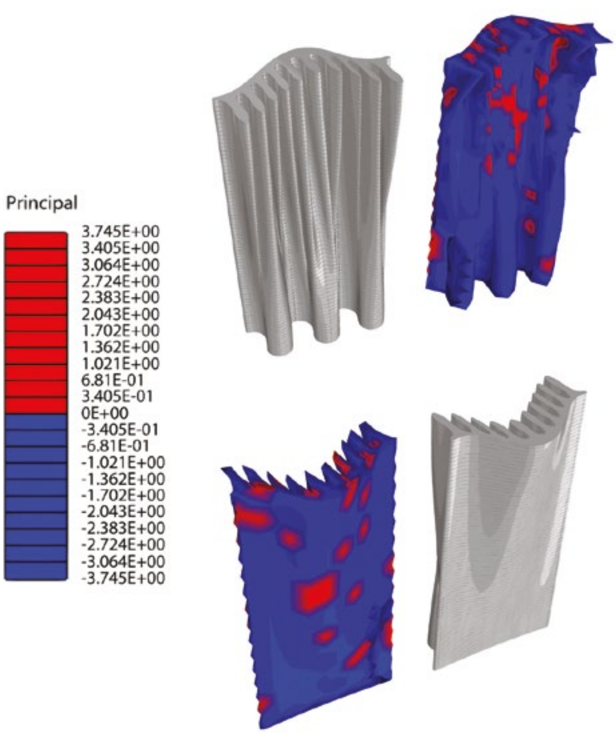

Figure 8: Principal stress distribution in the ribbed shell configuration, where positive (tensile) stresses appear in red and negative (compressive) stresses in blue. The ribbed geometry effectively redistributes loads, reducing high-stress concentrations and enhancing overall structural performance.

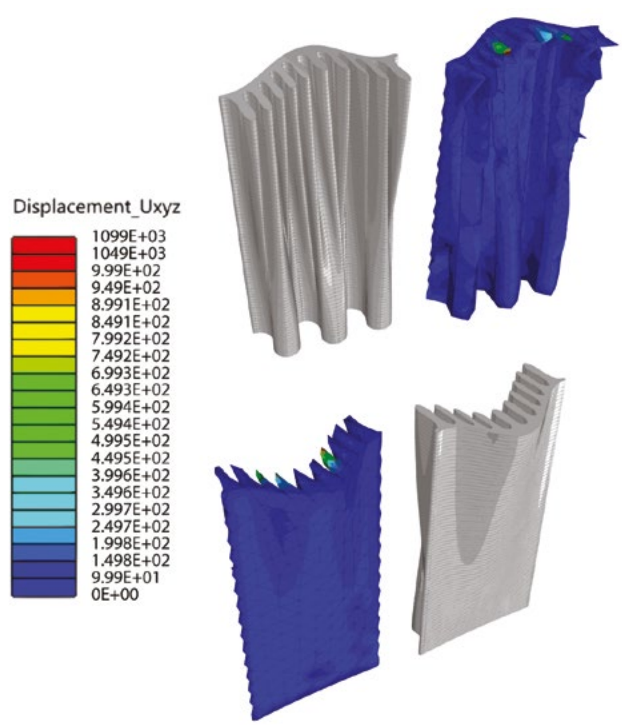

Figure 9: Displacement contours (Uxyz) for the ribbed shell configuration, illustrating deformation under applied loading. The color scale transitions from blue (minimal displacement) to red (maximum displacement, approximately 1.10×10^3, indicating that the ribbed geometry effectively minimizes overall deformation by improving load distribution and structural stiffness.

Figure 10: The initial spike in volume fraction quickly stabilizes, converging to approximately 0.975 by iteration 11, with total strain energy settling near 2.13×10^4.

Figure 11: Scaled prototype 1:10 3D printed using a laboratory robot at IAAC Institute for Advanced Architecture of Catalonia and nozzle 25mm, demonstrating controlled cavity design to reduce buckling and displacement.

Figure 12: Extrusion test of a 1:10 scale shell geometry using a 15 mm nozzle, based on a rib-reinforced computational design method.

stress trajectories. The combined use of Karamba3D and a standard FEA solver provides a robust validation mechanism: Karamba3D highlights qualitative stress patterns, while the FEA offers detailed quantitative results for accurate performance assessment.

Iterative Refinement and Validation

After each optimization cycle, the refined geometry undergoes FEA to confirm that strength, stiffness, and serviceability requirements are satisfied. The resulting stress and displacement fields inform further adjustments to the shell thickness, rib layout, or material distribution. This loop continues until the design meets the desired performance thresholds with minimal material usage. Finally, the optimized geometry is post-processed for manufacturability, ensuring that rib thickness, curvature, and overall shell dimensions are feasible for large-scale additive manufacturing.

RESULTS

In the final numerical results, The case 1 as shown in Figure 6 , and Figure 7, featuring converged to a volume fraction of approximately 0.95, indicating a 5% mass reduction while maintaining a relatively total strain energy of about 3.74×10^6. Correspondingly, the maximum displacement for this configuration was measured at around 4.76×10^2 showing higher potential of displacement accordingly high stain energy.

In contrast, as shown in Figure 9, and Figure 10. characterized by low principal stresses as shown in Figure 8, concluded with a volume fraction near 0.97 and exhibited minimum total strain energy of 2.13×10^4, along with a less maximum displacement of approximately 1.10×10^3. These results confirm that introducing ribbed shell as shown in Figure 9 reduces both strain energy and displacement under the same boundary conditions, thereby enabling greater mass savings without compromising structural performance. Suggesting effective distribution of load and higher overall stiffness.

REMARK CONCLUSION

A computational methodology for integrating topology optimization into the design processes of AM shell envelopes was developed by leveraging a C# based interface between SAP2000V24 and Grasshopper to simulate stresses based on standard data base, the approach interactive live simulation for model construction, structural analysis, and optimization, allowing for precise material distribution in shell designs, numerical evaluations underscoring the effectiveness of ribbed reinforcement in enhancing overall structural performance for construction 3d printing processes with earth-based materials. The use of SAP2000's Open Application Programming Interface (OAPI) and the *HybridOpt* Grasshopper plugin further streamlines these processes, enabling a practical and interoperable framework for both research and engineering applications. Future studies will expand on this work by refining ribbed reinforcement systems, thereby advancing the performance, feasibility, and scalability of 3D-printed architectural structures.

ACKNOWLEDGEMENT

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PARAMETRIC DESIGN AND DIGITAL FABRICATION OF CURVED ORIGAMI STRUCTURES REALIZED BY TWISTING ACTIVE PANELS

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Curved origami surfaces attract significant attention in architecture and engineering for the design of form-resistant modular structures. The realization of curved origami surfaces requires suitable structural design tools, manufacturing techniques, and construction methods. Here, a design workflow for the realization of curved origami structures assembled from flexible panels is proposed. Each flexible panel is realized as an interconnected array of beams according to the notable lamina-emergent torsion motif, with the result that panel bending is linked to the twisting of the beams. An analytical mechanical model for the bending of panels into cylindrical surfaces is described first. Then, such model is adapted to conical surfaces. This model is instrumental in determining the maximum achievable curvature of a cylindrical or conical flexible panel, and the corresponding stresses, as a function of the geometric features of the lamina-emergent torsion motif and of the material properties. The design workflow has two phases, the geometry design, in which a folded curved-origami geometry with corresponding crease pattern and surface ruling are chosen, and the design of the geometric features of the flexible panels. A parametric digital model was implemented using commercial software to carry out both phases, and two different literature computer codes were employed to simulate the origami folding process. The design workflow was demonstrated by the realization of physical prototypes using the laser cutting technology, and it can be applied at different scales to the manufacturing of curved origami structures. The case of an outdoor installation demonstrates the potential of the proposed design workflow for architectural structures.

INTRODUCTION

Since the 20th century, curved surfaces attracted significant attention in architecture and engineering for the design of form-resistant structures [1]; more recently, origami-inspired structures [2] and curved origami modular structures were also developed. The complex forms of curved origami surfaces require appropriate design methods and advanced tools for their realization as architectural and engineering structures. Several studies have been dedicated to the analytical geometric design of such surfaces. For example, an optimization procedure was proposed for the design and digital reconstruction of surfaces obtained by curved folding [3], and, a rationalized curved folding was presented to design origami mechanisms with one degree of freedom [4]. Moreover, a geometric mechanics model was described to study the folding behavior of curved origami [5], and, multilayered surfaces were assembled from rigid-foldable curved origami structures [6]. Furthermore, curved origami with multiple states were studied [7], a discrete elastic model was formulated for the structural analysis of curved origami [8], and systematic design methods for curved origami were presented [9]. At present, research on effective construction techniques for curved origami is still in an exploratory phase, and only a few literature studies have presented actual realizations

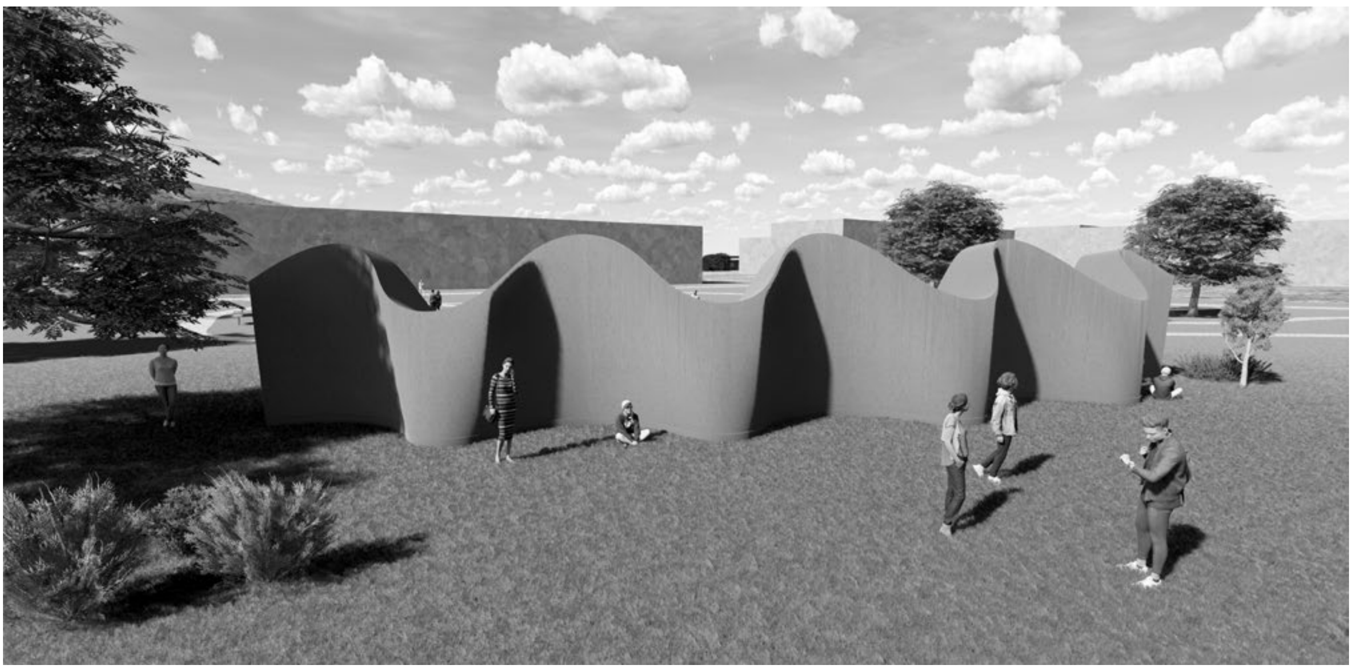

Figure 1: Computer view of an outdoor installation based on a curved origami surface.

or practical design solutions. For instance, the design and realization of two meter-scale prototypes folded and assembled from aluminum thin sheets were analyzed [10], a class of curved crease patterns were employed to create spatial structural enclosures composed of cylindrical and conical surfaces [11], and, accordion-like mechanisms obtained from flat plates with curved creases were designed to obtain corrugated spatial structures [12]. Here, a design workflow for the realization of curved origami structures assembled from flexible twisting-active panels is presented. Each panel is realized as a perforated plate according to the notable lamina-emergent torsion motif [13], in which an interconnected array of beams is subjected to torsion when the panel flexes. Lamina-emergent arrays were proposed to facilitate deployable mechanisms based on curved origami [14], and to assemble double curvature surfaces [15]. In addition, a lamina-emergent flexural connection was proposed [16], while laminar arrays were evaluated for the realization of compliant hinges for thick origami structures [17]. The presented methodology focuses on the use of an analytical mechanical model integrated with parametric modeling and physical prototypes. The mechanical model aims to determine the maximum curvature of the panels under cylindrical and conical bending, depending on the geometric features of the perforation pattern and the mechanical properties of the material. This model is then integrated with a parametric design tool with the aim of optimizing and automating the manufacturing process. Such approach has enabled the production of prototypes in various materials, particularly MDF (medium density fiberboard) and PMMA (polymethyl methacrylate), which have been analyzed to assess the impact of the perforation pattern on flexibility and strength. The use of the parametric and algorithmic simulation tool Grasshopper™ has allowed for a refined manipulation of the design variables and greater optimization of the final product. The proposed design workflow has two phases. The first phase consists of the design of the folded curved-origami geometry and of the corresponding surface ruling and crease pattern. In the second phase, the origami surface is subdivided into several panels, each with a perforation pattern whose geometric features are derived from the surface ruling and curvature. The design case of an outdoor installation, depicted in Figure 1, illustrates in detail the steps of the workflow. The paper is structured in two main sections: the first section presents the analytical mechanical model for the design of the twisting active panels, considering both the cylindrical and the conical surfaces; the second section presents the subsequent steps of the adopted design workflow referring to the case of an outdoor installation.

TWISTING ACTIVE PANELS

In this section, the analytical mechanical model of the twisting active panel is presented referring to cylindrical and conical bending, respectively. In both cases, the panels feature lamina-emergent torsion arrays aligned with the ruling of the surfaces. The model is instrumental in determining the maximum achievable curvature of the flexible panels and the corresponding stresses, as a function of the geometric features of the lamina-emergent torsion (LET) motif and of the material properties.

Cylindrical bending

For the analysis of the flexible panel for cylindrical surfaces, we adopt a modified version of the model presented by Oshima et. al [18]. A flexible panel is considered as an assembly of rigid blocks and linearly elastic beams, in which all beams undergo a twisting deformation when the panel is deformed into a cylindrical shape. Figures 2 (a) and (b) show a view of a bent panel and a detail of the LET motif, where we distinguish solid parts (beams and rigid blocks) and perforated parts. With reference to Figures 2 (c) and (d), the following parameters are identified. Each beam has width *t*, height *h*, and length *l*. The width of each rigid blocks is 2*d* and each perforated hole has width *s* and length 2(l+*d*). The distance between the axis of adjacent beams is *a*, while the distance between rigid blocks is *b*. The number of beams counted along the x-axis (y-axis) is 2*n* (*m*).

Two equal and opposite external couples of magnitude C are applied to the solid edges parallel to the beams' axis, as shown in Figure 2 (c) and (d). We assume that, in bending the panel in the $x-y$ plane, all beams are subjected to the same twisting moment M_T. Given that each rigid block carries the twisting moments of two beams (Figure 2 (e)), and that the panel can be split in two parts by sectioning *n* rigid blocks along the x-direction, the following equilibrium condition holds:

(1) $$C = 2M_T n \, .$$

The torsion stiffness s_T is given by:

(2) $$s_T = G\, J_T \, ,$$

where G is the shear modulus of the material and J_T is the torsion constant of the rectangular cross section of the beam, expressed by ($h > t$)

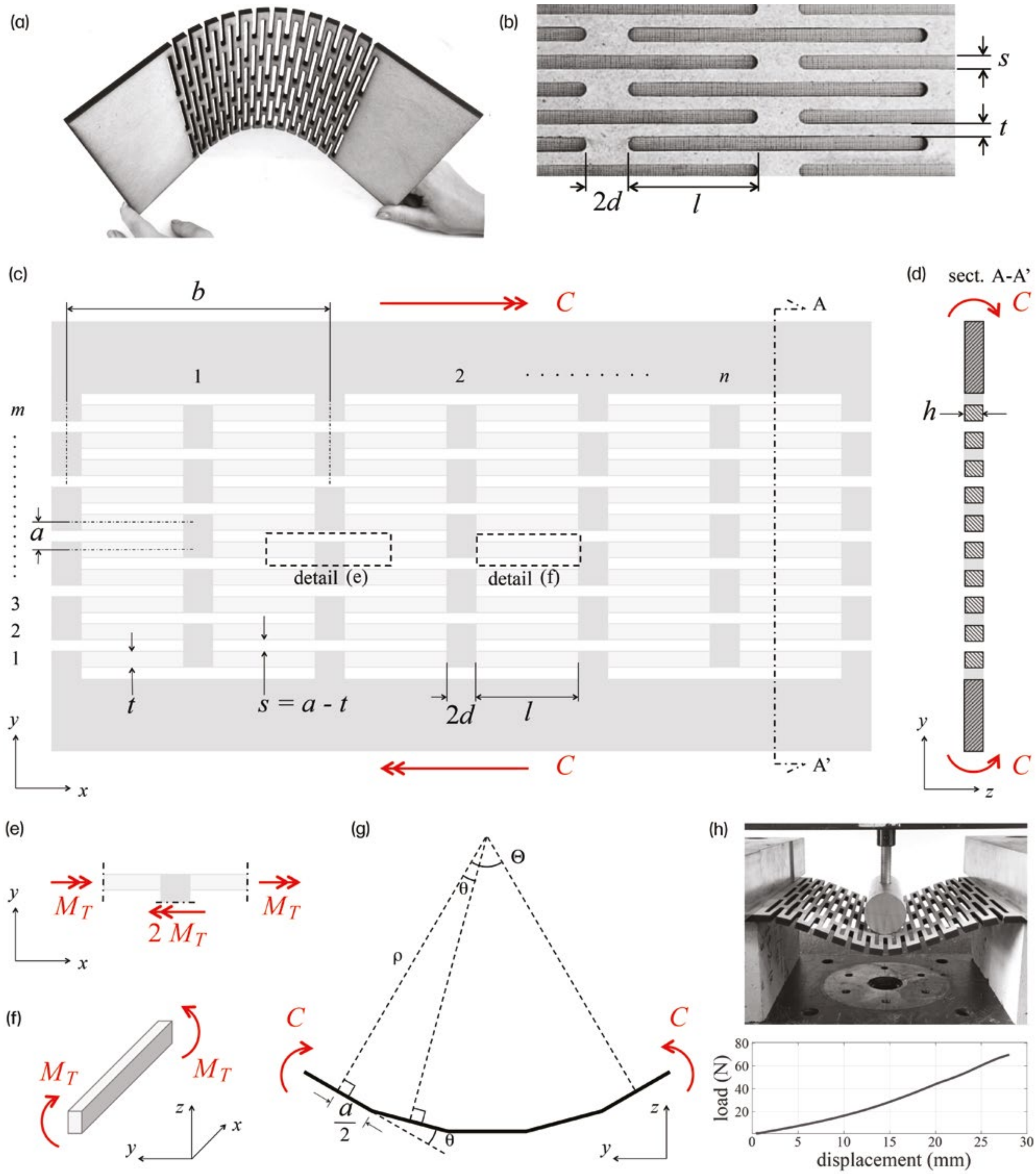

Figure 2: Cylyndrical bending model. (a) View of the flexible panel subjected to testing. (b) Detail of the LET motif. (c-f) Plan view, cross section, and details of the model. (g) Representative deformed configuration. (h) Sample subjected to flexural test and load vs. displacement curve. Conical bending.

(3)

$$J_T = \frac{1}{16} h t^3 \left(\frac{16}{3} - 3.36 \frac{t}{h} \left(1 - \frac{t^4}{12 h^4} \right) \right) .$$

The twisting angle, θ, associated to the twisting moment M_T, is calculated as:

(4)
$$\theta = \frac{M_T}{s_T} l .$$

This angle is also equal to the relative rotation between the rigid blocks of adjacent sections of the flexible panel, as shown in Figure 2 (g).

The action of the couples C that bend the panel induces the total relative rotation angle Θ between the two end sections, which can be computed as the summation of the relative rotation angles between adjacent sections.

We have:

(5)
$$\Theta = m\theta = m \frac{M_T}{s_T} l = \frac{1}{2} \frac{m}{n} \frac{C}{s_T} l .$$

A discrete curvature radius ρ, related to the twisting angle θ, can be obtained from the relation (cf Fig. 2, g)

(6)
$$\rho \tan \left(\frac{\theta}{2} \right) = \frac{a}{2} .$$

When θ is small, we can consider that tanθ θ and define the curvature κ as:

(7)
$$\kappa = \frac{1}{\rho} = \frac{\theta}{a} .$$

With this relation, using (1) and (4), the bending couple can be expressed as:

(8)
$$C = 2 n s_T \frac{\theta}{l} = 2 n s_T \frac{a}{l} \kappa .$$

Finally, the couple per unit width of the panel, 2, is calculated as

(9)
$$c = \frac{C}{nb} = 2 \frac{a}{b} \frac{s_T}{l} \kappa = \tilde{s}_B \kappa ,$$

In the last equality in (9), $\check{s}_B$ is the equivalent plate bending stiffness:

(10)
$$\tilde{s}_B = 2 \frac{a}{b} \frac{s_T}{l} .$$

These relations lay the foundation for understanding the behavior of LET panels when subjected to cylindrical bending. The correlation between the material's mechanical properties, the geometric dimensions of the panel, and the applied forces allow us to predict the panel's response in terms of curvature and twisting moment. The torsion verification of the rectangular cross section of the beams, according to standard regulations, allows the evaluation of the maximum radius of curvature ρ that the panel can achieve, which is fundamental to guarantee its structural integrity under load, ensuring that it can withstand expected stresses without incurring damage or permanent deformation. In particular, the maximum design shear stress for torsion is:

(11)
$$\tau_{tor,d} = k_{sh} f_{v,d} ,$$

where k_{sh}= 1 + 0.15 *h/t* is a coefficient taking into account the shape of the cross-section and $f_{v,d}$ is the design shear strength. The maximum shear stress for rectangular sections can be computed as:

(12)
$$\tau_{tor,d} = \alpha \frac{3 M_T}{t^2 h} ,$$

with α expressed by:

(13)

$$\alpha = 1 + 0.6095 \frac{t}{h} + 0.8865 \left(\frac{t}{h} \right)^2 - 1.8023 \left(\frac{t}{h} \right)^3 + 0.9100 \left(\frac{t}{h} \right)^4 .$$

By combining (4), (7), and (12), the design maximum curvature is obtained:

(14)
$$\kappa_d = \frac{t^2 h}{\alpha} \frac{k_{sh} f_{v,d}}{s_T} \frac{l}{a} .$$

A flexural test was conducted in the Laboratory of Structures, Tests, and Materials of the University of Rome Tor Vergata to evaluate the mechanical properties of the prototypes created. A sample in MDF with dimensions 400x220x6 mm (Figure 2 (a)) was prepared, which included solid parts at the edges to be clamped in the testing machine. The geometric parameters chosen for the LET motif for the sample are reported in Table 1 (cf. Figure 2). The sample was subjected to a gradually increasing displacement in the center until a displacement of 30 mm was reached (Figure 2 (h)), with a speed of the testing crosshead of 5 mm/min.

n	*m*	*a*	*b*	*h*	*t*	*l*	*d*
3	26	8mm	70mm	6mm	4mm	25mm	5mm

Table 1. Geometric parameters of the tested sample.

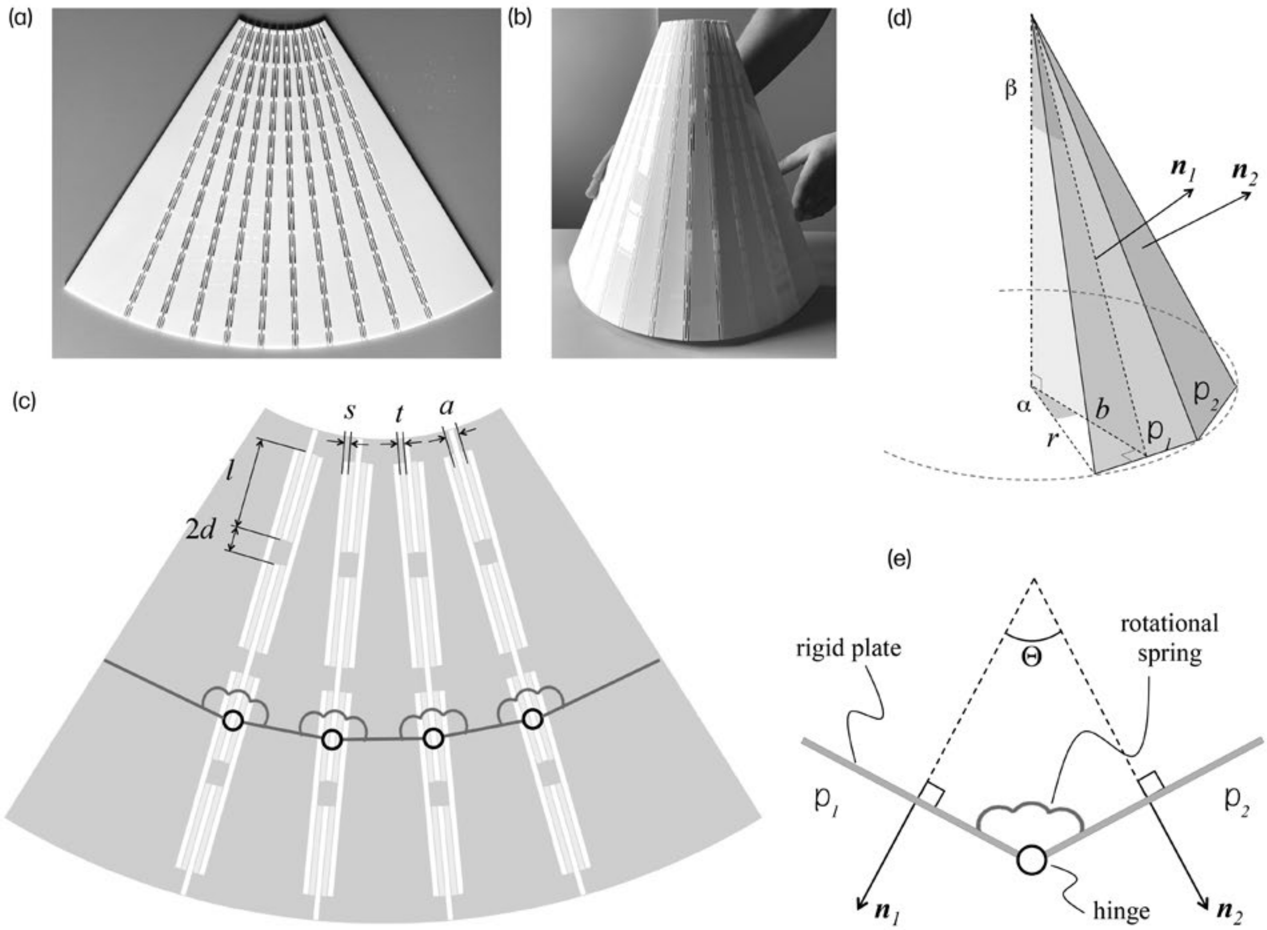

Figure 3: Adaptation of the LET motif to conical bending. (a,b) fabricated desktop prototype. (c) Schematization in rigid plates connected to each other by compliant hinges, realized by LET connections and modeled as rotational springs. (d) Deformed shape of two adjacent plates, geometric parameters and normal vectors. (e) Two adjacent panels connected by a compliant hinge sectioned by a plane containing the normals.

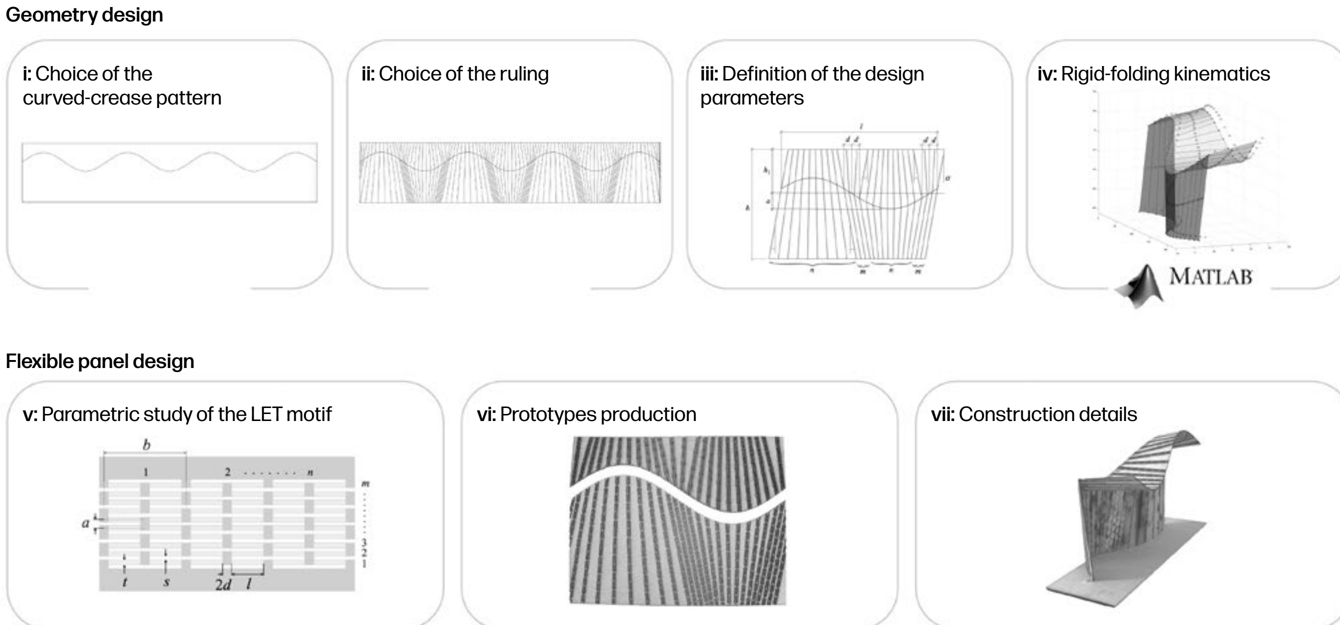

Figure 4: Design and production steps.

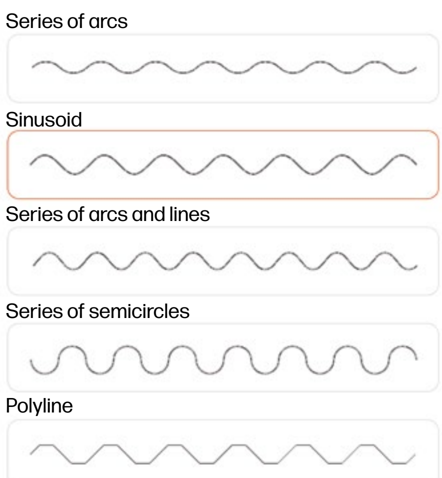

Figure 5: Typological studies of the curved crease (in red the chosen curve).

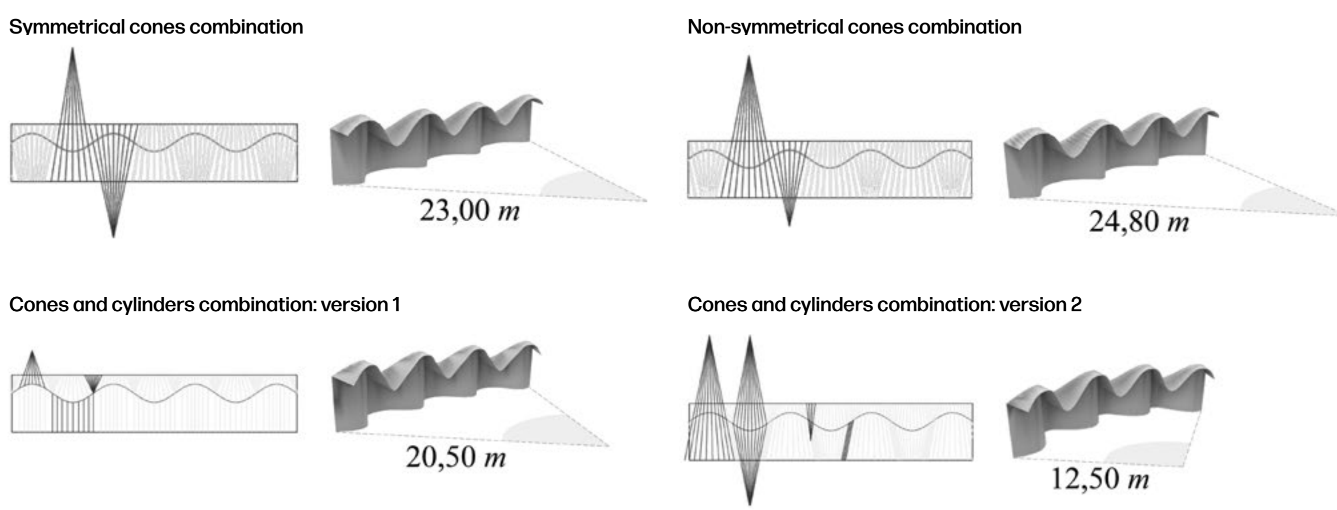

Figure 6: Study of the ruled surface pattern (in red the chosen pattern).

At the beginning of the test, under a small imposed displacement, the deformation of the sample is comparable to that of a clamped-clamped beam loaded in the center, showing a predominant bending behavior and linear response. As the imposed displacement increased, the panel began to stretch in-plane, and a nonlinear stiffening effect was observed from the force vs. displacement curve. The initial stiffness was calculated from the data of the flexural test and compared with that obtained analytically. The stiffness calculated using two test data points near the origin, (δ_1, f_1), (δ_2, f_2), is $k_{test} = (f_2 - f_1)/(\delta_2 - \delta_1) = 1.484\ ^{10-3}$ kN/mm. The analytical calculation considered the stiffness constant for the transverse displacement at the midpoint of a clamped-clamped Euler-Bernoulli beam, given by $k_{an} = 192\, s_B / l^3_B$, with $s_B = nb\, \check{s}_B$ (cf. (9)) and $l_B = ma$. By considering the value G = 800MPa for the shear modulus of the MDF, the calculated stiffness is $k_{an} = 2.174\ ^{10-3}$ kN/mm. This value is higher than that measured in the test, as it should be, reflecting the fact that the deformation of the portions of the panel corresponding to the rigid blocks in the model is neglected.

Conical bending

In the conical case, the rows of perforations are placed along the generatrices, leaving large unperforated trapezoidal areas that act as rigid plates (Figure 3 (a,b)). The panel is considered an assembly of rigid plates connected to each other by compliant hinges realized by LET connections and modeled as rotational springs (Figure 3 (c)). The rotational stiffness of such springs can be computed from (8) in terms of the parameters that define the LET connection. The deformed configuration of two adjacent rigid plates can be described by the parameters depicted in Figure 3 (c,d): α, β, r, b, and Θ. The angle Θ formed by the normal vectors $\mathbf{n}_1$ and $\mathbf{n}_2$ of two adjacent panels can be calculated in terms of α and β from the following expression,

(15)
$$\cos\Theta = \frac{\mathbf{n}_1 \cdot \mathbf{n}_2}{\|\mathbf{n}_1\|\|\mathbf{n}_2\|} = (\cos\beta)^2 \cos(2\alpha) + (\sin\beta)^2 .$$

Using a Grasshopper™ code it was obtained a parametric LET perforation pattern featuring rectangular holes with rounded corners. The slits pattern follows the ruling of the conical surface. The desktop prototype shown in Figure 3(a,b) was produced with the laser cutting machine on a Perspex panel of 300x400x3 mm, and it is characterized by 10 lamina-emergent arrays, each with three rows of 1mm slits, spaced 1.5mm apart and 2.5 cm long.

Design application

This section focuses on the design of a curved origami outdoor installation composed of flexible twisting-active panels. The design process exploits parametric design tool Grasshopper™, Origami Simulator [19], and MATLAB codes.

The design workflow, shown in Figure 4, articulates in two main phases: the study of the geometry of the curved origami (Steps i-iv) and the design of flexible twisting-active panels (Steps v-vii), exploiting both cylindrical and conical surfaces (Figure 4).

The geometry of the outdoor installation is modular. The base module refers to a curved origami composed of a single wavy mountain fold on a rectangular shape. The repetition of the base module suggests the study of a sine wave-like curve contained in an oblong rectangle. The subsequent definition of the folded configuration comprises the parametric study of the sine wave-like curve and of the related ruling surface. The design of the flexible panels follows the definition of the ruling and develops through the study of the LET slit pattern.

Geometry design

The study of geometry is organized in four steps and is described below. The combined use of the Grasshopper™ code and Origami Simulator supports steps i and ii, i.e., the parametric study of the crease pattern and the simulation of the fold. Steps iii and iv require the use of GrasshopperTM and a MATLAB code to simulate the kinematics of the rigid folding.

i. *Typological studies of the curved-crease pattern*: The geometry of the mountain fold curve is defined by comparing a series of arches, a series of arches and lines, a series of semicircles, a polyline and a sinusoid (Figure 5). A Grasshopper™ code is used for the parametric analyses of each curve and for the definition of the related ruling surface. A simulation of the fold is, thus, conduced, exploiting Origami Simulator, for each of the five crease patterns. Result of the simulation shows the sinusoid as the best option for the mountain fold.

ii. *Study of the ruling surface pattern*: The definition of the design ruling is conducted combing portions of cylindrical and conical surfaces. The study follows an iterative process based on the combined use of a Grasshopper™ code, for the parametric definition of the mountain fold curve and the ruling pattern, and Origami Simulator for the simulation of the fold. As shown in Figure 6, four combinations of cylindrical and conical surface are considered: a symmetrical combination of conical surfaces; a non-symmetrical combination of conical surfaces; the combination of two types of conical surfaces and one type of cylindrical surface; the combination of three types of conical surface and a band-like cylindrical surface.

The four considered combinations are compared through the simulation of the fold: as shown in Figure 6, the folded structures, related to the four combinations of conical and cylindrical surfaces, are inscribed respectively in a 23.00 m-radius circle, in a 24.80 m-radius circle, in a 20.50 m-radius circle, and in a 12.50 m-radius circle. Result shows, thus, the latter configuration as the most effective in terms of folding capabilities.

iii. *Definition of design parameters*: For the sinusoid the considered geometrical parameters are the amplitude A and the period L. The other relevant design parameters for the panel dimensions and the surface ruling are illustrated in Figure 7. According to the architectural functionality of the structure, the period L was taken equal to 6.30m while the wave amplitude A is equal to 0.70 m. In the dimensional assessment, the balance between the elevation and the cantilever span of the structure is considered: according to the defined value of the sine wave amplitude, the cantilever span range from $H_1 - A$ = 0.85m to $H_1 + A$ = 2.25 m; the minimum value of the structure elevation was set as $H - (H_1 + A)$ = 2.30m and, consequently, the maximum value of the pavilion elevation is $H - (H_1 - A)$ = 3.70 m. The ruling of the conical and cylindrical surfaces is defined respectively by the parameters *N* and *M* that indicates the number of subdivisions. The parameter D determines the width of the cylindrical surface, and it is equal to 0.50 m. The angle α corresponds to the inclination of the ruling and it is equal to 11 degrees.

iv. *Rigid-folding kinematics:* Given that the underlying mechanical model in Origami Simulator accounts for the out-of-plane elastic deformation of the tiles, the accuracy of the folding process and of the folded geometry was verified by adopting the rigid-origami MATLAB™ calculation platform introduced and detailed by Micheletti et al. [20, 21]. The interoperability of Grasshopper™ and MATLAB™ was exploited to export the origami data from Grasshopper™ and import it into the MATLAB™ code. The crease pattern of the rigid origami was obtained by segmenting the sinusoidal crease and by considering the subdivisions of the ruled surfaces as shown in Figure 7. Such rigid origami has one degree of freedom. The folding process was simulated numerically by imposing the folding angle at the curved crease. The output geometry of the rigid folding process is depicted in Figure 8.

Flexible panel design

The design of flexible panels develops through the study of the LET arrays. It consists of three steps supported by the use of Grasshopper™ and laser cutting technology to produce physical prototypes. The three steps are described below.

v. *Parametric study of the LET pattern*: A Grasshopper™ code is developed for the parametric study of the LET motif and the production of prototypes exploiting laser cutting. The code allow to assess the following parameters: *N* and *M*, as the numbers of subdivisions of the conical and cylindrical surfaces respectively (Figure 7); *l* as the length of the beams, *t* as the width of the beam; *s* as the width of the slits; 2*d* as the width of the rigid blocks; *a* as the interaxis between the beams, and *b* as the interaxis between the rigid blocks (Figure 2). The geometrical construction of the LET pattern develops through the offset of the curves composing the ruling, controlled by the *s* and the *t* values, and the subsequent subdivision of the same curves according to the value of the *l* and *d* parameters. The code comprises, eventually, the possibility to control the fillet of the slits corners, which is necessary to avoid stress concentration effects.

The base module of the designed structure corresponds to the period of the wave curve and is composed of four panels. As shown in Figure 9, to obtain the four panel the base module is divided vertically and horizontally. The vertical subdivision corresponds to the end of the conical surface and the start of the cylindrical band. The horizontal subdivision corresponds to the mountain fold curve: the lower part forms the wall-panel while the upper part the cantilever-panel of the designed structure. Dimensions and geometry of the four panels are reported in Figure 9. The first wall-panel *is a conical surface:* the value of the *N* parameter (number of subdivisions) is equal to 35. The second wall-panel is composed of two side sectors of cylindrical surfaces – for both sides the value of the *M* parameter (number of subdivisions) is equal to 9 – and a central sector of conical surface – with the same value of *M*. The first cantilever panel is a conical surface while the second cantilever panel is composed of two side-sector of cylindrical surfaces and a central sector of conical surface, with corresponding values of *N* and *M*. For all panels, the value of the *l* parameter (length of the beams of the LET motif) is equal to 88mm and the values of the C parameter (width of the beam) and the *t* parameter (width of the slits) are both equal to 4 mm; the *d* parameter (half-width of the rigid blocks) is equal to 6 mm.

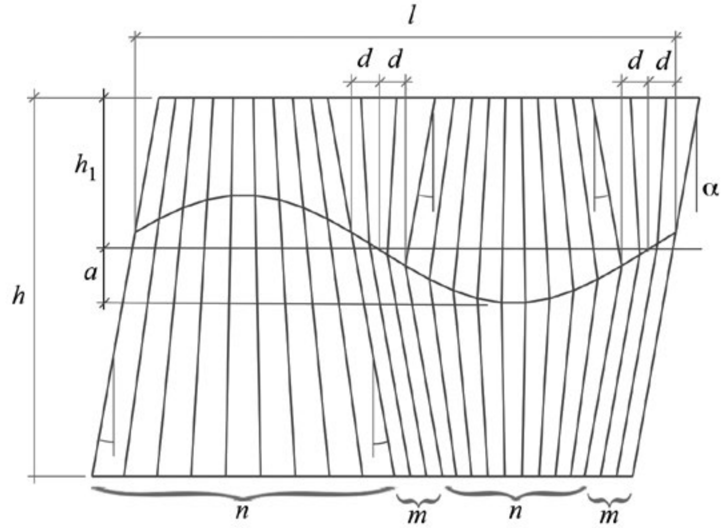

Figure 6: Study of the ruled surface pattern (in red the boundaries between conical/cylindrical rulings).

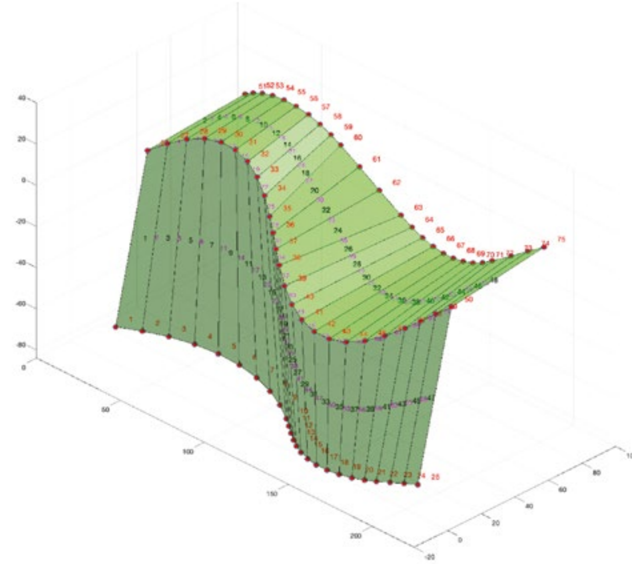

Figure 8: Rigidly folded configuration of a representative module simulated in the MATLAB™ calculation platform described Micheletti et al. [20, 21].

a)

b)

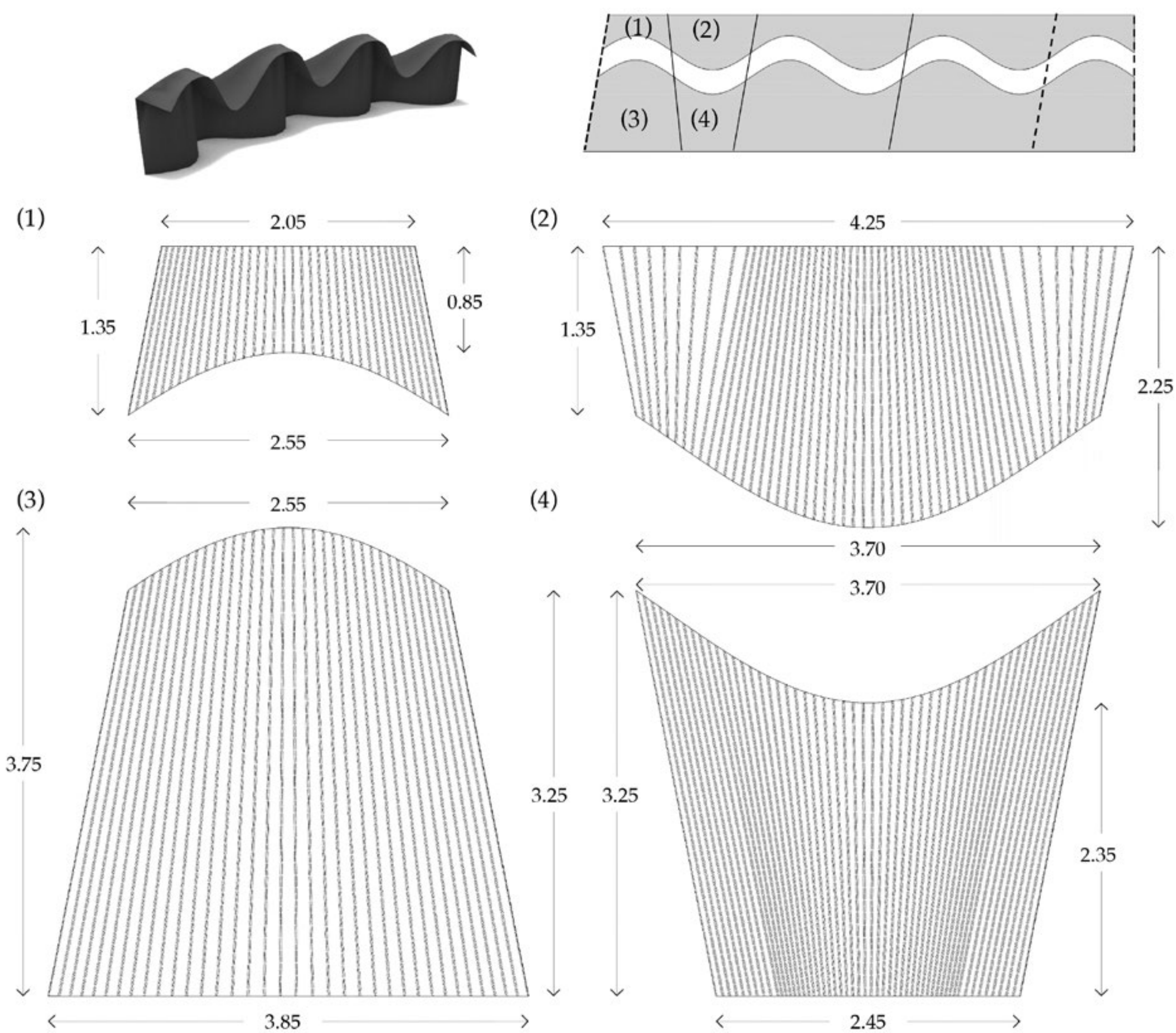

Figure 9: The four base panels of the structure. Dimensions are expressed in meters.

vi. *Prototype production:* An appendix of the Grasshopper™ code was developed to produce the 1:10-prototype of the designed structure, taking advantage of laser cutting technology and FDM desktop 3D printing. The material choose for the laser cut prototype is a 4 mm thick MDF panel. The prototype is composed of two panels. As shown in Figure 10, the two panels are obtained subdividing a rectangular module – 0,46 m height and 0,62 m wide – of the designed structure on the mountain fold curve: the lower part forms the wall panel while the upper part the cantilever panel. Both the wall and the cantilever panels are composed of two conical side portions and central cylindrical band. For the adopted slits pattern the value of the *l* parameter (length of the beams of the LET motif) is equal to 19mm and the values of the *t* parameter (width of the beam) and the *s* parameters (width of the slits) are both equal to 2 mm; the *d* parameter (half-width of the rigid blocks) is equal to 3 mm. To assure the folding of the structure, the horizontal connections between the wall and the cantilever panels is composed of a set of steel hinges located on the mountain fold and fixed on the panels by bolts. The Grasshopper™ code was implemented to produce a further small-scale prototype exploiting the FDM desktop 3D printing technology. This small scale prototype, shown in Figure 12 aims to explore further alternative of the joints between the wall and the cantilever panels, avoiding steel connections and exploiting tensile bands.

vii. *Construction details:* The production of the prototypes supports the study of construction details of the designed structures. The study focuses, in particular, the connections composed of reversible devices in order to assure the disassembly and the re-usability of the designed structure. A reversible dry joint is designed for the vertical connection between the four panel, exploiting a C-shape-element fitted into the slit of the LET motif at the ends *of the panel.* The C-shape element can be produced exploiting laser cutting – as it is in the presented prototype – or can be substituted by a standard profile in steel. To assure the folding of the structure, the horizontal connections between the wall and the cantilever panels is composed of steel hinges located on the mountain fold and fixed on the panel by bolts. The connection to the grounds are also designed exploiting commercial steel plates – functioning as basement – fixed removable bolts. A possible alternative to the hinge joints between the wall and the cantilever panels is represented by the use of tensile bands as a stitching within the two elements.

CONCLUDING REMARKS

In this study, the design of curved origami structures assembled from twisting active panels was performed, with a particular focus on the analytical and experimental characterization. The exploration included the development of LET patterns for ruled cylindrical and conical surfaces and the study of the interaction between ruled and folded geometries. The adoption of a methodological approach that combines an analytical model with parametric modeling tools facilitates the production of physical prototypes, exploiting digital fabrication technologies, in order to assess the folded configuration and the building details of the origami structure. The investigations revealed the effectiveness of the proposed methodological approach in analyzing the curvature and in the sizing of the twisting-active panels, which feature a pattern of perforations, intended for ruled surfaces, in both cylindrical and conical configurations. Parametric modeling has proven to be a reliable mean for rapid prototyping and has provided indispensable visual support in the architectural design process. Moreover, the use of laser cutting as a production methodology of the prototype has favorably contrasted with conventional methods, such as 3D milling, in terms of time and cost of the process. In this sense, the study envisaged also the production of the prototypes with 3D printing techniques, exploiting the already produced Grasshopper™. From a structural design perspective, the study introduced a scalable design and realization method for lightweight modular structures, adaptable to various application fields, including interior design, construction, morphological structures, and robotics [22,23]. Particular application examples in the building sector are: centering systems for modular reiforced concrete shells based on ruled surfaces, lightweigth structures for curved façades, and acoustic barriers for open spaces. The dimensions of the modules are chosen so as to satisfy the size of the laser cutting machine, supporting the design of elements of reduced size easy to transport and to assemble without the need of heavy machinery. The proposed analytical approach permits the fast selection of the thickness and curvature of the elements to fulfill the structural requirements, supporting customized production based on digital fabrication. However, several important challenges remain, particularly the development of a mechanical model for conical and tangential developable surfaces in relation to various cutting patterns. This area requires additional research to further refine the design and address the remaining technical challenges by advancing the field of state-of-the-art structural design.

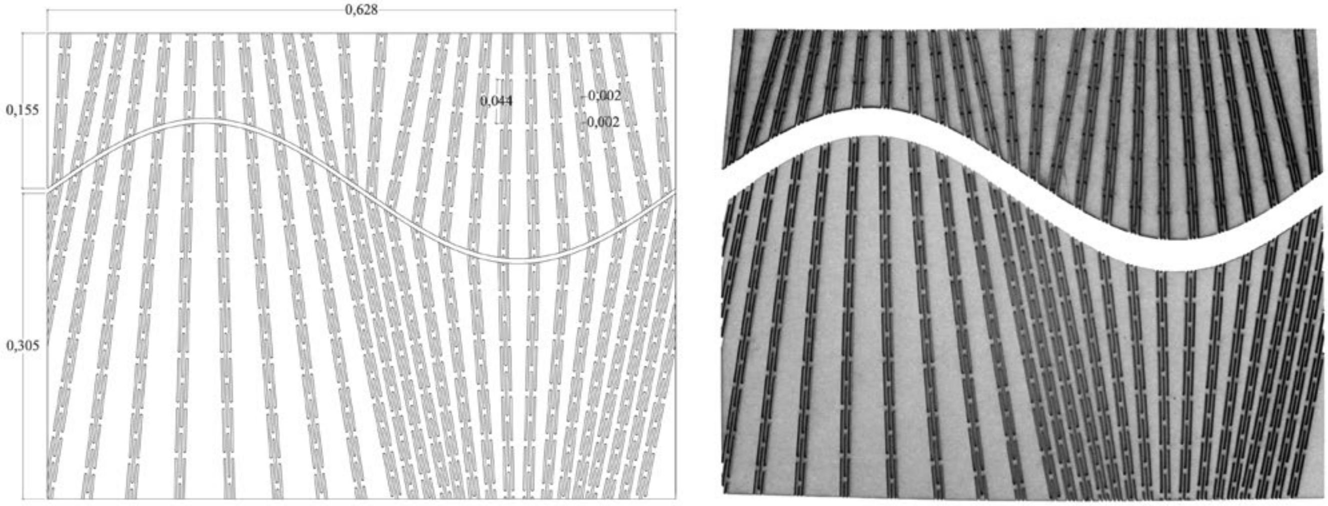

Figure 10: Prototypes panels (scale 1:10).

Figure 11: Laser cut prototype (scale 1:10) connected with hinges to reproduce a module of the outdoor installation.

Figure 12: 3D printed small scale prototype.

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3D-PRINTING HIGH PRECISION COMPONENTS OF BUILDING SCALE-MODELS FOR WIND TUNNEL TESTING

Giacomo Scrinzi
Enrico S. Mazzucchelli

The article explores the transformative role of 3D-printing in architectural and engineering research, with a specific focus on its application in producing scaled models for wind tunnel testing of photovoltaic (PV) systems. The study highlights how 3D-printing enables the creation of prototypes which can be essential for the investigation and optimisation of structural designs. A case study explores the use of advanced 3D-printing technologies in the fabrication of extremely accurate and intricate items, such as instrumented PV modules incorporating hollow channels for pressure measurements, gear, racks, and sliding components. The integration of PolyJet and SLS technologies combined with tailored materials and meticulous post-processing treatments (such as sandblasting, spray polymer coating, alkaline solution dip, etc.) ensured high precision, functionality, and adaptability. This approach significantly reduced production time and costs while enhancing the reliability of experimental results. The findings underscore the potential of 3D-printing to revolutionise experimental methodologies, facilitating rapid design iterations and fostering innovation in sustainable and resilient building design.

INTRODUCTION

3D-printing has emerged as a transformative technology across numerous industries, including architecture and engineering, by enabling the creation of accurate, intricate, and highly customisable prototypes. Among its most fascinating applications is the development of scaled models for laboratory testing, such as wind tunnel experiments [1]. These models are instrumental in studying the aerodynamic behaviour of structures, identifying potential issues related to wind resistance, vibrations, and structural stability, and ultimately refining design solutions.

Wind tunnel testing is a cornerstone of modern engineering and architecture, providing critical insights into the interaction between buildings and environmental forces [2,3]. Whereas even minor deviations in geometry can significantly influence test results and the accuracy and reliability of these tests depend heavily on the quality of the prototypes used, although 3D-printed model can nowadays ensure great reliability as conventional models [4,5]. In this context, 3D-printing offers unparalleled advantages, allowing for an accurate yet quick and cost-effective the reproduction of complex geometric features and intricate details that are often essential to replicate real-world conditions [6].

Moreover, 3D-printing supports a wide range of techniques and materials [7], including resins, polymers, and composites, which can be tailored to meet specific project requirements. This flexibility ensures that prototypes not only mimic the geometric characteristics of the structures they represent but also possess the necessary mechanical properties to withstand testing conditions, such as aerodynamic loads and high-speed airflow.

One of the most significant benefits of 3D-printing is the efficiency it brings to the prototyping process. Traditional methods, often involving manual craftsmanship, were time-consuming and expensive, requiring specialised skills to produce even basic models. In contrast, modern 3D-printing technologies enable the rapid translation of digital designs into physical models, often within a few days or just hours. This accelerated timeline empowers engineers and architects to iterate more effectively, incorporating feedback and optimising designs with minimal delays.

In wind tunnel experiments, 3D-printed models are required to be provided with an ultra-high precision as they are generally equipped with sensors and other instrumentation to measure aerodynamic forces and pressures with high precision. These measurements yield valuable data that guide the design of safer, more efficient, and better-optimised structures. The ability to produce high-precision models through advanced 3D-printing techniques [8] represents a significant leap forward in experimental methodologies, offering both enhanced accuracy and reduced costs.

CASE STUDY

Nowadays, the integration of photovoltaic (PV) systems on buildings to enhance energy efficiency has become an increasingly relevant topic, especially in the context of large roofs. These surfaces, if properly designed and utilised, can ensure significant energy productivity, contributing substantially to sustainable energy solutions. To maximise the energy output of such systems, it is essential to install solar arrays with an optimal orientation and tilt angle designed for the specific latitude of the site. This precision ensures that PV modules capture the maximum possible solar radiation throughout the year.

However, in practical applications, PV modules are often installed coplanar to the roof slope, since higher tilt angles, though more efficient for energy capture, are associated with increased wind-induced loads transferred to the support structure of the PV modules and since the reference regulations [9] do not always provide exact specifications for such conditions. While this approach simplifies installation and reduces structural stress, it also typically leads to a compromise in energy productivity.

To provide designers with more information about the wind loads on rooftop PV modules, wind tunnel tests were carried out [1] on a 1:10 scale model of a representative building featuring a quadrangular footprint and a flat roof situated at a height of 10 meters (Figure 1). The model incorporated standard PV modules arranged in parallel 8 strings (each is ~20 meters long in real scale), tilted with angles varying between 5° and 30°, assumed to be parallel to the slope direction and/or the building edges. The design of the model required to feature specific adjustments to allow for the investigation of the influence of several geometric parameters, i.e. the tilt angle of the strings (5° to 30°), the spacing between rows (0.6 to 1.15 m), the wind direction (all-round), and the clearance between the panel's bottom edge and the roof plane (15 to 30 cm), as shown in Figure 2.

Therefore, the strings length had to be enough to avoid the affection of pressure coefficients by corner vortexes. According with the previous studies, a 12 photovoltaic modules string (1920 mm long) was considered adequate.

Moreover, increasing the side spacing between adjacent modules has proved having minimal effect on the force coefficients, while the wind load coefficients increase as the rows spacing is increased. For this reason, the model strings were designed without providing any gap between modules.

Furthermore, for roof-mounted arrays the wind load coefficients appeared to decrease with increasing perimeter gap from the building edge. It was then conservatively chosen one standard distance of 1.5 m from the edge, which can be considered the minimum to allow the integration of a perimetral gutter and a maintenance walkway.

Each PV string needed to be equipped with a total of 56 pressure taps in correspondence of 28 positions distributed along both the upward and downward sides of the modules (Figure 3), to be connected to pressure sensors via tubes embedded in the module thickness, enabling accurate measurements of wind-induced pressures. For symmetry, half of each string featured instrumented modules, while the other half comprised solid components (Figure 1).

Given the complexity of the adjustable components and the precise instrumentation required for the PV modules, the small scale of the model posed significant manufacturing challenges. Traditional production methods would have struggled to achieve the necessary level of detail, precision, and adaptability within a reasonable timeframe and budget. In this context, 3D-printing proved to be a transformative solution, offering unmatched accuracy and flexibility. This advanced manufacturing technology not only enabled the creation of intricate parts with fine tolerances but also facilitated rapid prototyping and adjustments, ensuring that each component met the stringent requirements of the experimental setup.

Moreover, 3D-printing allowed the integration of complex features, such as internal channels for pressure taps, directly into the module design, which would have been nearly impossible with conventional techniques. By reducing production time and costs while maintaining exceptional precision, 3D-printing played a pivotal role in the success of the wind tunnel tests, enabling a faithful and reliable

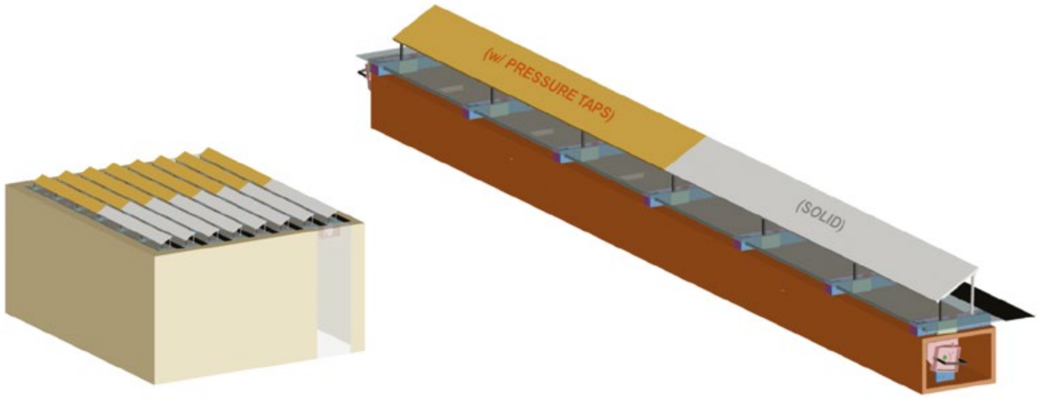

Figure 1: Representative building 1:10 scale model.

Figure 2: Typical geometric parameters for flat-roof mounted PV strings.

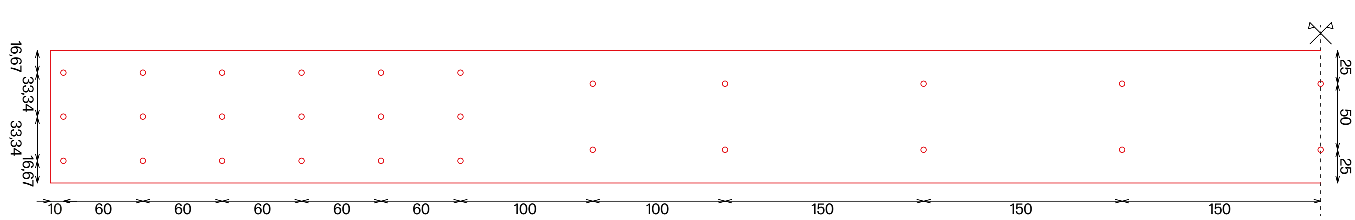

Figure 3: Pressure taps position on the half string.

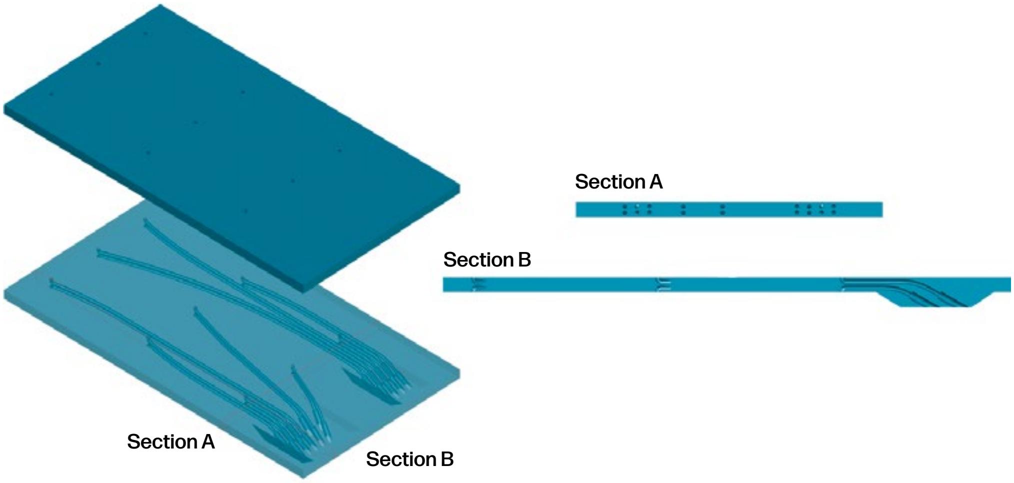

Figure 4: Virtual model of 1:10 instrumented solar panel provided with pressure taps and connection tubes. Panel cross-sectional thickess is 5.0 mm; tubes diameter and minimum wall thickness are 1.0 mm; minimum curve radius is ~10.0 mm.

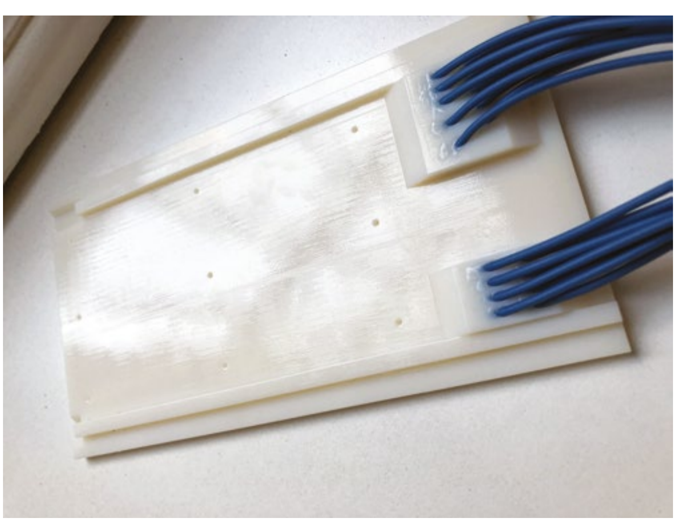

Figure 5: 3D-printed instrumented solar panel, fully assembled.

Figure 6: PolyJet 3D-printing of instrumented solar modules with embedded pressure tubes.

simulation of real-world conditions. Its application in this context highlights its potential as a game-changing technology for the development and optimisation of advanced experimental models in engineering research.

The model's components were manufactured using a variety of advanced printing technologies, each chosen based on the specific requirements of the individual parts.

The most complex items were the instrumented solar modules, which presented a significant challenge due to their intricate design, which needed to accommodate high-precision features within a very limited thickness of just 5 mm. Within this thin profile, two rows of hollow tubes were integrated, each with a diameter of 1 mm and a wall of 1 mm (Figure 4). These tubes served the critical function of connecting pressure taps (holes), strategically positioned on both main surfaces of the panel, to an end collector. The collector itself was meticulously designed to allow the insertion of silicon tubes, which were subsequently fixed in place and sealed using an adhesive and then connected to pressure sensors, forming a complete system for pressure monitoring (Figure 5).

The primary technical challenge in creating these modules lays in achieving hollow geometries with an extremely high precision. The tubes had to maintain a constant cross-section along their entire length and be completely airtight to prevent any errors in the pressure readings. Any deviation from these stringent requirements could compromise the functionality of the pressure system.

In order to meet such requirements, the modules were fabricated using a Stratasys Objet260 Connex3 3D-printer, a machine equipped with advanced multi-material jetting photopolymer technology, commonly referred to as PolyJet. Such technology operates by jetting ultra-thin layers (down to an impressive 16 μm) of a liquid photopolymer onto the build platform. These layers are then progressively cured using UV light and bonded together (Figure 6), resulting in parts with outstanding precision and extremely fine and precise wall thickness. The printing material used for the modules was a simulated polypropylene, known as "digital" polypropylene, obtained by combining VeroWhitePlus and Agilus30. This combination provided the printed components with good mechanical properties and a smooth surface finish that met the design specifications.

To create hollow geometries, SUP706 support material was utilised. This material, intended to be soluble in alkaline cleaning solutions, filled the internal cavities during the printing process, ensuring structural integrity and accurate dimensional control. However, removing the support material proved to be a particularly labour-intensive process. Each printed item required multiple cycles of cleaning to ensure the internal cavities were completely free of residual material. This process involved soaking the parts for 5 minutes in a heated and agitated cleaning station containing a solution of 2% sodium hydroxide and 1% sodium metasilicate. Following the soaking, a fine nylon monofilament, with a diameter of 0.5 or 0.7 mm, was repeatedly inserted into each tube to mechanically dislodge any remaining material, and then the ends of the tubes were rinsed using a high-pressure water jet to ensure complete removal of the support material. Concerning the whole cavities cleaning process, 3D-printing proved to be the best approach since it allowed initially a quick and easy optimisation of tubes geometry in terms of section diameter, wall thickness, and curve radius in order to comply with the strict quality and precision requirements. Eventually, each printed model was dipped for 30 seconds in a 15% glycerol solution for strengthening.

In contrast, other components of the model, such as the dummy solar modules and parts of the adjustment mechanisms with simpler geometries, were fabricated using an alternative production method better suited to their functional and design requirements. These components were produced with an EOS Formiga P110 selective laser sintering (SLS) 3D printer (Figure 7). This method employed PA12 nylon powder as the base material, chosen for its excellent mechanical properties, including robustness and resistance to wear, making it an ideal choice for structural components expected to endure prolonged use.

Once the printing process was completed, the components underwent an accurate post-production sandblasting process. This step was essential for removing residual powder from the items' surface, ensuring a clean, smooth and uniform surface appearance, crucial for the functionality of the parts, and preparing the components for subsequent treatments.

Certain components with specific performance requirements, such as gears, racks, and other sliding elements belonging to the adjustment mechanisms required additional treatments to enhance their operational efficiency. These parts were treated with a spray-applied polymer coating, which smoothed the surface further, significantly reducing roughness due to the printing process, and sealed the material, making it non-absorbent to preventing the ingress of contaminants. The latter treatment was intended to prepare the surface for the application of a PTFE lubricant, which was crucial for minimising friction in areas where low resistance was essential. The combination of the smooth, sealed surface and the PTFE lubricant significantly improved the performance of the sliding components, ensuring reliable and consistent operation.

This enhanced functionality was critical for enabling smooth transitions between different string configurations. Each configuration adjusted the tilt angle and bottom clearance of the solar modules through an operation driven on each string by a system of 2+1 NEMA17 stepper motors (Figure 8) controlled by an Arduino shield which provided accurate control and synchronisation across the system, ensuring accurate positioning.

Eventually, 3D-printed parts were integrated with other components (i.e. envelope panels and strings support frames produced by CNC milling wooden panels, and strings top covering panels made by laser cutting PMMA slabs) to create the whole model (Figure 9).

The careful integration of materials, fabrication methods, and post-processing treatments ensured that all model's components met the stringent requirements for functionality and precision of this advanced prototype.

CONCLUSIONS

In conclusion, the integration of 3D-printing into architectural and engineering research has proven to be a groundbreaking development, particularly in the production of scaled models for laboratory testing. This technology has revolutionized the approach to experimental studies, offering unprecedented precision, adaptability, quickness and cost-effectiveness. The ability to create complex geometries, replicate intricate details, and incorporate functional features directly into the prototypes is unmatched by traditional manufacturing methods.

The application of 3D-printing in the wind tunnel testing of photovoltaic systems demonstrates its transformative potential. The intricate instrumented PV modules required for these tests, featuring hollow channels, pressure taps, and thin-walled structures, were made possible only through advanced 3D-printing techniques such as PolyJet technology. The exceptional precision of this method ensured airtight tubes and geometries that met the strict requirements for accurate pressure measurements. Simultaneously, the flexibility to produce robust yet simplified components, like adjustment mechanisms and dummy solar modules, using SLS technology highlighted the versatility of 3D-printing in handling diverse manufacturing challenges.

Furthermore, the use of tailored materials, such as digital polypropylene and PA12 nylon, allowed for the optimisation of mechanical properties while meeting the specific demands of different components. The post-production treatments, including cleaning, surface finishing, and lubrication, further exemplified the adaptability of 3D-printing to achieve high-performance standards in demanding applications.

The success of this project underscores the pivotal role of 3D-printing in advancing experimental methodologies. By significantly reducing production time and costs, while maintaining the highest levels of accuracy and functionality, this technology has proved to enable engineers and researchers to rapidly iterate design refinements in order to eventually gather reliable data for real-world applications. By bridging the gap between digital design and physical prototyping, this technology is reshaping the possibilities of sustainable, efficient, and resilient building design.

Looking ahead, 3D-printing is bound to become an even more crucial part of engineering workflows. Such technology, as demonstrated by its great contribution in the creation of high precision components for experimental testing, is not only a manufacturing method, but also a catalyst for innovation, enabling the creation of safer, more efficient, and better-optimised structures.

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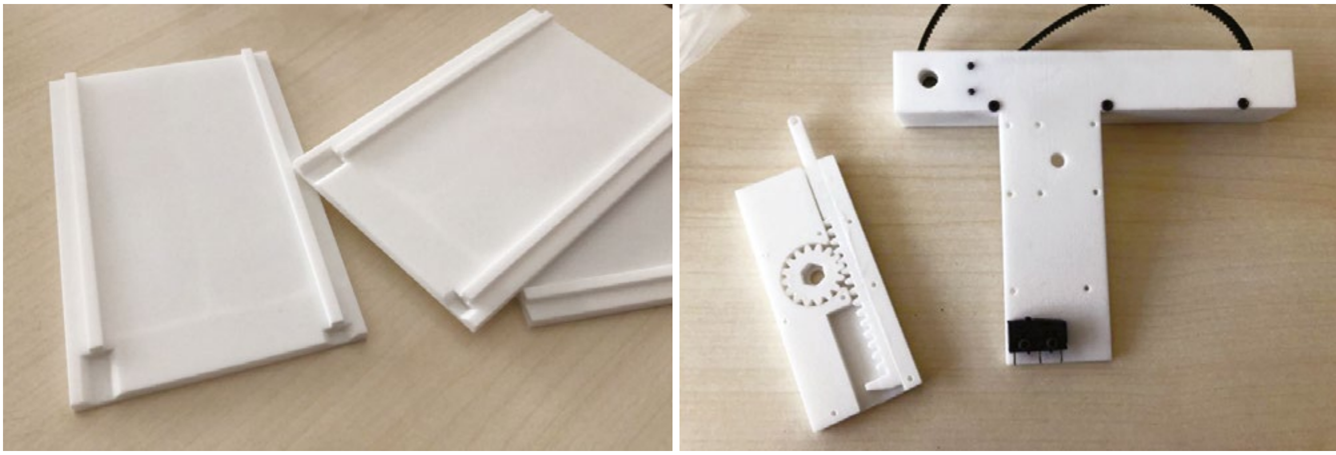

Figure 7: SLS 3D-printed solid PV modules and example of adjustment system components.

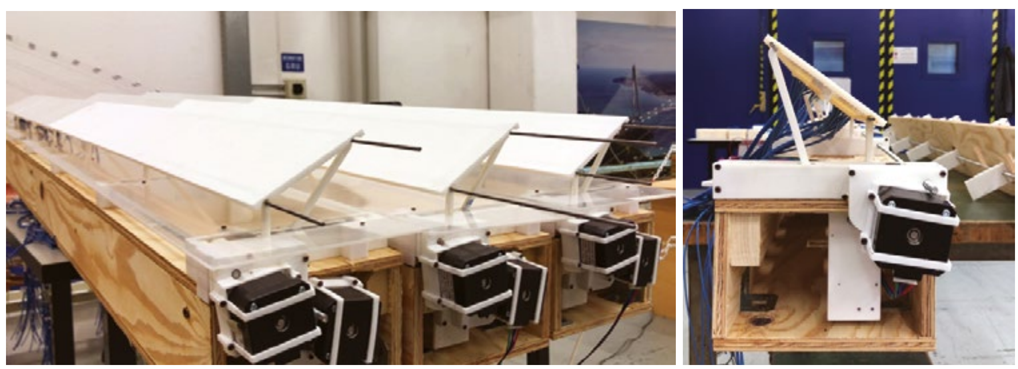

Figure 8: Scale model strings assembled and equipped with stepper motors for adjustment capability.

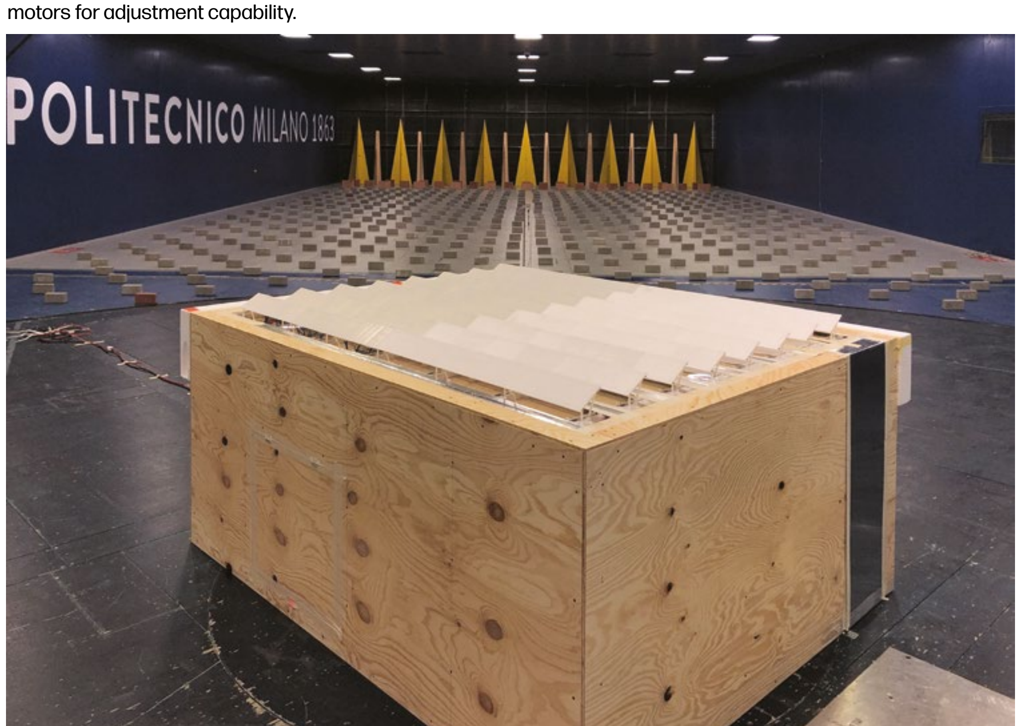

Figure 9: Scale model fully assembled inside PoliMi boundary layer wind tunnel.

4. *Advancing* Manu— facturing

Advanced manufacturing is posing the basis for the full transformation of the construction industry, with the integration of cutting edge technologies, including 3D printing and real time monitoring with robotic platforms. These last can include a large set of robots that collaborate to assemble construction systems, or can become enabler for multifunctional structural and construction systems with advanced long term performance. Automating the construction sector has been of interest of many for the last decades [1], having a large uptake in the recent decades thanks to the affordability of collaborative robots (cobots), and to the mainstreaming of language programs that facilitate the programming and interaction also from less IT experts.

Today, we are witnessing multiple line of developments, with industries working on the automation of traditional construction sites [2], such as the Shimizu Corporation, that launched in 2018 the Shimuzu smart site to integrate robotics and digital technologies into construction workflows, by adopting robots for doing repetitive tasks such as transporting material around the construction site, brick laying [3], woodwork (Figure1), steel welding, and rebar tying of reinforced concrete systems. The Smart Site system [4] integrated, moreover, robots with AI driven management system, via a central platform that monitors task progress, worker positions, and equipment status in real-time.

On the other side, the development of Additive manufacturing at a large scale has seen the adoption of gantry crane systems for the deposition of 3D printing materials for full scale houses, and of tuned extruder systems for robotic arms for the 3D printing deposition of clay, steel alloys and biogenic materials, for high performing components. The growing geometrical, architectural and technological complexity of the obtainable systems has sparked the interest in employing robotics also for assembling dry-construction systems. In the field of architectural robotics, we are, indeed, witnessing to a growing interest in adaption of robotic platforms for the development of the circular systems, designed and fabricated to be assembled and disassembled multiple times, and that can potentially be reconfigured in new geometrical systems.

This last approach see automation as an enabler for advancing circularity of construction, as it can enhance efficiency, precision, traceability, and adaptability. Robotic can indeed be used for assembly and disassembly systems, it can be used for selective deconstruction for material and components recovery, storing information in QR codes and APRtags can allow for recognition of the product information, understand of the life-cycle performances, and cataloguing for future uses.

This approach are allowing multiple innovations [5] across the field of architecture, with the development of innovative systems and components that can be fabricated through robotic assembly and or depositions; in the field of off-site and design for manufacturing and assembly (DfMA), with advancements of mobile construction shops, far from site and/ or near sites, within flying factories; in the field of mechanical engineering, with the creation of new end effectors for tuning infinite construction tasks; in the field of simulation [6] and data sensing, with the development of sophisticated digital twin for having real time data about changing environments, in which the robotic platform will operate. Last, but not least, innovations are growing in the strategic field of "human-robot collaboration", as it is thanks to the direct interaction of human flexibility and intuition, and the precision and repeatability of robotic systems that the AEC field will be transformed.

However, while sensing and digital twins are developing fast, and are finding already large real applications, the robotic architectural is still pretty much into the prototyping phase, with still much to be done. This is opening up the question: Is "robot – oriented design" the right way to go? Or, perhaps, shall we move towards "material-robot systems", in which both robots and building materials/components are designed in coordination [7]? Initial propositions of this last approach have started to appear for some brick laying, and fiber winding by multiple cooperative small robots. But, most likely, the field is in full expansion, and it is imagined that the materials and systems that would be best used in a fully automated construction site has still to be discovered.

Lastly, it is, most likely, in the integration of material-robot systems, human-robot collaboration, and digital twins, that the real transformation of the AEC will be seen.

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ROBOTIC MANIPULATORS AS ADVANCED MANUFACTURING AGENTS FOR LASER-CUT CONSTRUCTION SYSTEMS

Sam Wilcock
Ornella Iuorio

Robotic manipulators are transforming advanced manufacturing by allowing for the precise manufacture of intricate geometries and the direct transfer of digital data to physical materials. Recent work in the Architecture and Structures Lab (ASLab) of Politecnico di Milano has explored how these technologies can be integrated into laser-cut construction systems, particularly into workflows that connect digital design with robotic assembly. A series of methods are described to optimise designs for handling by manipulator arms, employing reachability analyses and assembly sequencing to ensure that construction is feasible. The stability of structures during scaffold-free assembly has been verified using R-funicularity and Coupled Rigid-Block analysis, with the goal to minimize reliance on temporary scaffolding during robotic assembly. Online control systems have been explored to improve on more widespread offline planners, utilizing fiducial markers and point cloud data to improve accuracy and robustness of automation. These workflows significantly enhance the fabrication and assembly of interlocking panelised structures, allowing for precise placement and a reduction in errors as well as providing early-stage design feedback. A case study with laser-cut timber sheets demonstrates cost-effective manufacture of contour crafted panels and their robotic assembly. This research pushes forward the integration of online planning for robotics in manufacture, providing a scalable workflow for automated assembly. With this, it is shown that through incorporating sensor feedback it is possible to improve manufacturing process precision and lessen the need for manual calibration.

INTRODUCTION

As architects and makers, robotic arms provide exciting opportunities in the realm of digital fabrication and manufacturing. The inherent precision of such digitally controlled systems allows high repeatability of tasks and enables the direct realisation of complex designed CAD forms. In the realm of additive manufacturing, they allow non-planar deposition which was previously infeasible with traditional cartesian printing machinery, providing benefits in layer adhesion, printed component strength and surface quality [1] and allowing sequential printing of multiple components. Recent work is also focusing on embedding components within conformal geometry [2] which is made possible through mounting 3D printing end-effectors to manipulators.

In assembly and subtractive manufacture, too, there are opportunities to be exploited with manipulator arms. Traditional assembly lines in the automotive industry have long made use of industrial arms for highly repetitive tasks, although typically such robotic cells are trained to function on a single task within the manufacture process. Better exploitation of the potential for arms allows their use as multi-functional agents able to complete multiple different tasks; for example, work of ICD Stuttgart constructed a multi-purpose manufacturing unit for the construction of the BUGA Wood Pavilion which was capable of manipulating cassettes, assembling them from plate components, milling and drilling [3].

Solutions integrating robot control into the CAD environment exist already (e.g. KUKA|prc [4] and HAL [5, 6]). As noted by Gandia et al. however [7], these tools work on input curves for the robot end-effector to follow, and these curves have to be created manually. With COMPAS FAB [8], the Gramazio Kohler research group allowed for connection between CAD and popular robotics middleware the Robotic Operating System (ROS) [9]. Using ROS, which is what many roboticists build hardware drivers and interfaces for, it then becomes possible to access sensor data and process feedback, something else which is lacking in the common workflows for CAD. In addition, tools such as MoveIt [10] provide capabilities for robot path planning and collision avoidance (shown being used for motion planning in Figure 1).

In this chapter, a series of software tools and pipelines are described which have been developed with the purpose of easing the digital design, fabrication, and robotic assembly of panel structures. Steps towards providing the designer with initial knowledge of robotic capabilities and translational freedom of designs are given, which allow the design of interlocking structures within the reach space of manipulator arms. Explorations in structural analysis are also described, such that structures may be constructed with minimal use of external scaffolding. Furthermore, a workflow has been developed based on the ROS middleware which allows for online planning and adaptation of motion planning for structural assembly. Finally, a series of experiments into this assembly process incorporating sensor feedback are discussed.

DESIGNING FEASIBLE STRUCTURES FOR ROBOTIC ASSEMBLY

Within the Architecture and Structures Lab (ASLab) at Politecnico di Milano, one stream of research has been focused on the development of CAD plugins and software to make design for robotic assembly simpler for the end users. While there exists a potentially infinite design space for a discrete panel structure typology which can be created within CAD, actual feasible designs which can be realistically manufactured and assembled by a robot arm represent a small subset. Indeed, the capabilities of the available robot arms (e.g. maximum reachability, carrying weight, ability to reposition the base), as well as geometrical design constraints (e.g. interlocking and interfacing between parts), and mechanical properties of the structural systems can limit the panel structure typologies that can be feasible for robotic assembly. In the following sections, pathways to overcome these limitations (or to work within these constraints) are discussed.

Reachability analyses

The working capabilities of manipulator arms are not necessarily intuitive for humans. Whilst many manipulators are based on human arms – with a set of joints, often a shoulder, elbow and wrist they are similar in many ways – however the configuration of a manipulator's joints is fundamentally different. The standard number of joints employed to be able to have a solution for any position and orientation within the reachable radius of the arm is 6, in order to cover cartesian poses, i.e. positions in X, Y, Z, and the respective rotations of roll, pitch and yaw. However, some arms have less joints than this, and many have an additional joint, to allow redundancy in having multiple solutions. Additionally, the physical structure of the arm can cause less reachable zones, where the arm cannot pass through itself. Further, singularities cause issues – where two or more of the joints are aligned in such a way that controlling the end effector to a local Cartesian pose can cause wild, dangerously fast motions.

In order to gain a quantitative understanding of the workspace for manipulator arms, the concept of the reachability analysis was developed, as described by Bergerman and Xu for point reachability [11] and extended to include pose orientation [12]. This method has been implemented by the ASLab group for Grasshopper modelling. First, an inverse kinematics numerical solver was created to find joint angles given a cartesian pose using a popular software package IKFast [13]. With this analytical solver available, it becomes trivial to test whether a pose is reachable or not.

To provide a metric probability of a pose being reachable, the volume around the manipulator was divided into a regular grid of points. For each point, a series of orientations was tested, sampled regularly using a Fibonacci sphere, and the number of reachable orientations found for each point. Then, the reachability score (for each 3D point is:

(1) $$R = \frac{N}{D} \#\left(\text{ SEQ (\textbackslash* ARABIC 1 } \right)$$

Where N is the number of reachable orientations, and D is the number of orientations tested. These reachability scores can then be stored and used to score a geometric design for its overall reachability. Figure 2 shows the analysis applied to a parametric brick wall, which was scored using a fitness function to completely disallow unreachable bricks and maximise both the reachability and number of bricks; green locations in the figure indicate highly reachable regions and bricks, whilst red regions are close to singularity with few reachable orientations. The fitness score could then be used with an evolutionary solver to find some highly performant designs within the workspace.

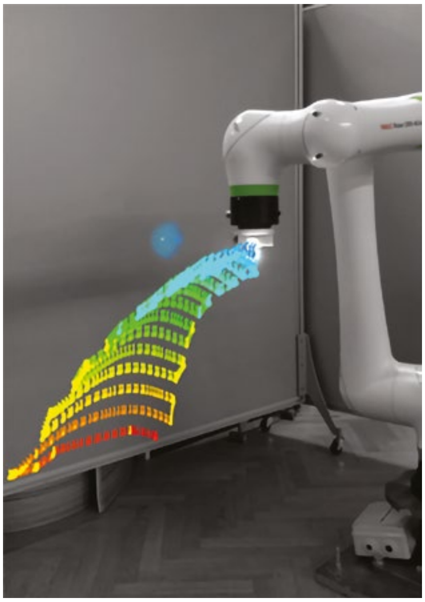

Figure 1: Control of a Fanuc manipulator arm to follow an example printing path, using online planning and control. An LED is attached to the end-effector, and a post-processing OpenCV script provides a long exposure light painting effect.

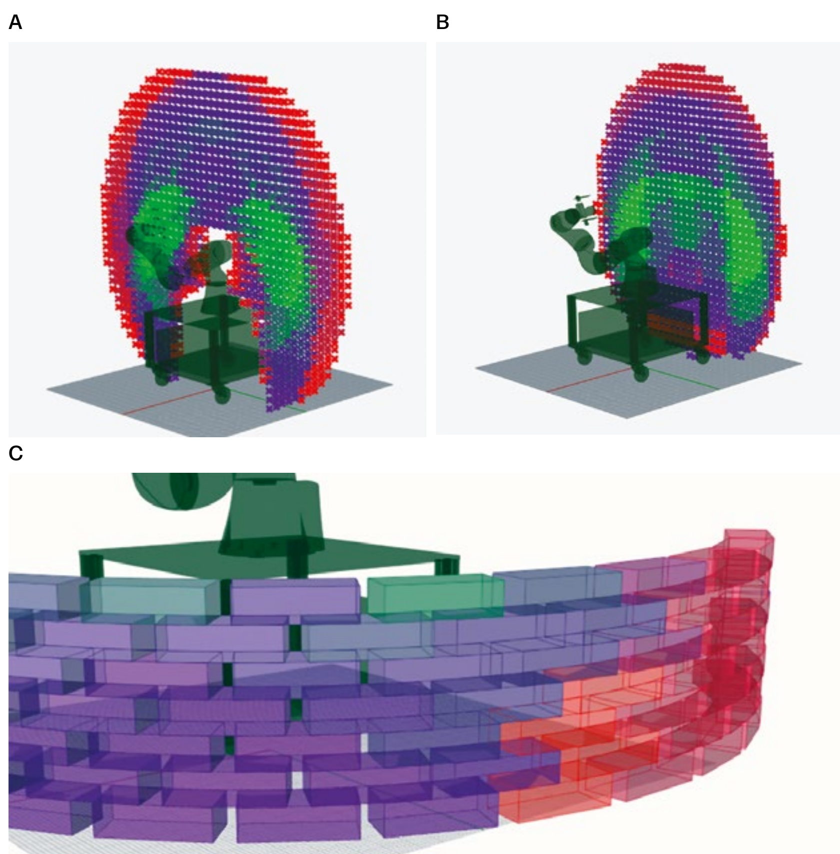

Figure 2: Reachability scoring for understanding construction feasibility, with green indicating high reachability and red, low reachability: (A) Reachability about a central slice in line with the manipulator base; (B) Reachability further out along the robot base's X-axis; (C) reachability metrics applied to a parametrically designed brick course.

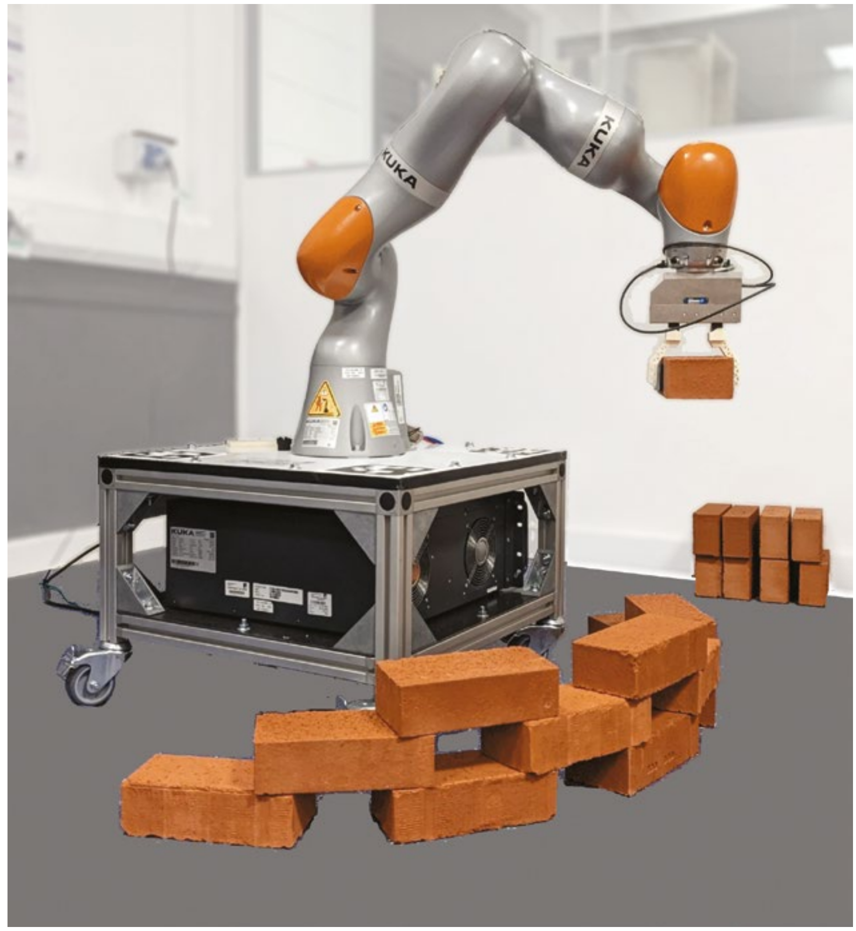

Figure 3: Brick wall construction with end pose data transferred from parametric CAD design.

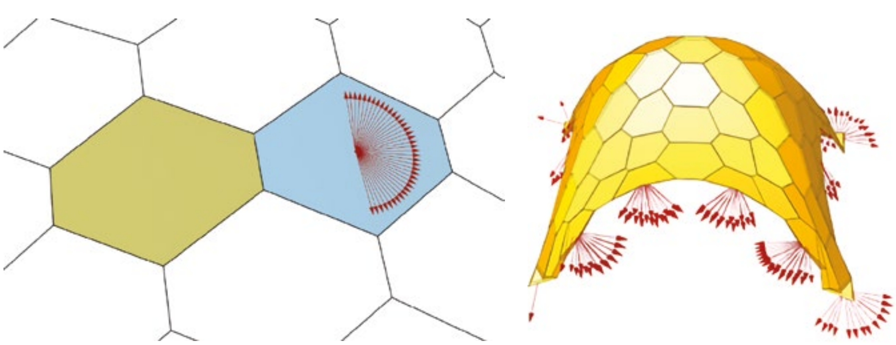

Figure 4: Kinematic analysis of a structure based on mating geometry: (A) The “free directions” of the clear blue panel are displayed relative to the opaque yellow panel; (B) The free directions within an example panel structure, accounting for all neighbouring panels.

Assembly sequencing

When designing interlocking panel components, there are two, contradictory goals. The first is that the panels should constrain each other in such a way that the structural integrity is guaranteed once assembled, for example preventing sliding motions, particularly those that could occur through gravity. When done correctly, it is possible to design structures without external fixtures, making disassembly much simpler at the structure's end of life [14]. On the other hand, it is also important that the designed structure is not over-constrained: it is perfectly possible to design a structure in CAD that is locked together in such a way that it could not realistically be assembled or disassembled, like a sliding puzzle with no solution.

One possible solution to this problem lies in Non-Directional Blocking Graphs (NDBG) [15]. First take a set of "free" or unblocked directions between a reference panel and one of its neighbours, which are vectors through which an infinitesimally small translational movement could be made without hitting anything (Figure 4A). If the set intersection of these vectors, and the similar sets describing free directions between the reference panel and all neighbours within the structure is found, it will describe the translational freedom of the reference panel, and thus possible directions through which it could be removed from the structure. If, at any given partial set of the structure's panels, we apply this to every element, we can locate the panels which are loosest, i.e. have the highest translational freedom (Figure 4B) [16]. Incorporating precedence constraints, i.e. ensuring that panels are only inserted if they have at least one neighbouring panel already within the structure, allows defining the possibility to insert each panel at any configuration of the partially assembled structure.

Given the free directions of the panels within the fully assembled design, it is possible to search for assembly sequences through iteratively removing elements from the structure and recalculating the free directions. This "backwards assembly planning" is a common search method [17] as it works from the most constrained state to the least, reducing the potential amount of sequences to test. This is important as the number of potential sequences to brute force test would otherwise be , where is the number of panels – for a realistic number of elements this number is extremely high and hence computationally expensive.

Different selection strategies can be chosen for selecting the next panel to remove, which gradually frees more panels in its neighbourhood. Successful full assembly sequences were found for the design in Figure 4 based on simply selecting the panel with the largest number of free directions. However, for other designs with realistic constraints found in the later integrally joined designs in this chapter, disassembly testing found many "dead ends" where the panels were interlocked and the search required restarting. In these cases, a semi-stochastic approach (giving some random choice to the next panel to remove) more quickly found a feasible sequence for the disassembly, and hence assembly of the geometry.

The utility of such a tool is not simply limited to panels, but it can be applied to any assembly of volumetric geometries which are connected through matched surfaces between neighbours. For example, one possible use case would be to combine such tools with structural analyses, to additionally select assembly sequences by those which most improve the structural integrity [18].

STRUCTURAL ANALYSES FOR SCAFFOLD-FREE ASSEMBLY

In addition to the robotic assembly feasibility of structures, their stability should also be considered. Panel or shell structures tend to require temporary falsework during construction to prevent their collapse, since they are often designed for global stability (ability to self-support once fully assembled) but not for local stability (self-supporting when partially assembled). This can be problematic when pursuing robotic assembly, as the supports will often obstruct and reduce the possible motions.

A number of different solutions to the falsework issue have been explored in the literature. One approach explored by Parascho is the use of a secondary arm to provide temporary support to the structure whilst adhesive or fixtures are placed [19]. This however creates its own set of issue; besides requiring additional expensive hardware, motion planning for multi-arm systems is more complex than for a single arm if they are moving at the same time. Others have created collaborative situations where a human operative takes the place of the secondary robot as temporary support or works to apply permanent fixing during the robots holding phase [20]. However, this type of human robot collaboration can be more prone to the accumulation of errors.

An alternative approach has been taken within the ASLab, where the focus has been on creating dry-stacked structures, i.e. without fixtures or adhesives to create structures that can be more easily disassembled. In order to do this, structural mechanics has been leveraged to solve the local stability issue through 2 methods, with one approach focusing on flexural and material effects, and the other focusing on contact and friction effects [21].

R-funicularity as post-processing tool for FEA

Gabriele et al. [22] introduced the use of an eccentricity metric for shell structures, as an indicator of how close the structure is to funicularity in different locations. By taking the ratio of bending moments to tensile forces and comparing to a factor of the material thickness, it can be shown whether the structure is dominated by compression effects (in which case the load is directed through the structure and is stable) or bending effects (in which case the structure will need external support). An initial finite element elastic analysis is undertaken on the design, before a postprocessing step is undertaken to calculate eccentricities. Additionally, the use of joints between panels can infer a tensile limit force [23], which has been calculated for dovetail joints and used to predict the stability of test arches and shells [21].

In recent work from the ASLab, the formulation was modified slightly to give a simplified visual representation of this eccentricity, also showing regions of contraflexure and where compression changes into tension, allowing a fast visual inspection to show expected failure regions to focus on adding additional support. Models were manually exported in FEA software for analysis, before being reimported back into Grasshopper for post-processing (see Figure 5A).

Due to the use of the elastic FEA, the R-funicularity approach works well for predicting the deflection of panels caused by flexural rigidity and could be well applied to a variety of materials and manufacturing processes where the material properties can be estimated. It is primarily defined for the fully assembled case, as the concept of funicularity makes little sense where there is no membrane through which to distribute the load acting on the material. Additionally, it relies on the assumption that the structure acts similar under load to a continuous geometry, as setting up an elastic analysis factoring in joint interactions is not a trivial task.

Coupled Rigid-Block Analysis (CRA)

In an attempt to account for the mechanics of the discretised panel typology of structure, an alternative approach has also been utilised. The coupled rigid-block analysis (CRA) of Kao et al. [24] is a methodology where masses are assigned to the discrete elements, in addition to friction coefficients at element interfaces. In a simplified form, based on a classical rigid-body mechanics formulation, it is possible to apply equilibrium conditions with friction constraints into an optimisation problem (Figure 6). If a solution to the optimisation problem can be found where there are no tensile forces, the structure can be assumed stable. In the original article by Kao et al. introducing CRA, the rigid block formulation was extended to include rigid body displacements, allowing for more realistic constraints to be added, such as removing friction constraints and normal forces when part surfaces move too far apart.

Kao et al. demonstrated that their analysis was suitable for shell forms including the well-known Armadillo shell from the Block Research Group [25] and for concave interface geometries, making it ideal for the integral dovetail joints being experimented on in the ASLab. The analysis was implemented through Python to be easily run from within Grasshopper (Figure 5B), allowing fast stability analysis of partially assembled structures.

A CALL FOR PROCESS FEEDBACK AND ADAPTIVE CONTROL

While manipulator arms tend to be highly repeatable – also called precise, meaning that they will repeatedly move close to the same location when given the same command. They are often not, however, accurate, meaning that the position they go to is not necessarily the requested one. This can have many causes, such as inaccuracies in the kinematics calibration, nonlinear effects in motors and operating temperatures to name a few.

As previously mentioned, a majority of the available CAD plugins for robot control are based on offline planners – a set of instructions is generated to complete a task, and then often generated to a robot manufacturer specific list of instructions to be executed similarly to how G-code works for traditional printing devices. While this works well for these Cartesian devices, there is a widespread issue of how to continue a print (or in this case, an assembly) if something goes wrong or needs recalibrating during the program's runtime. Additionally, due to the repeatability/precision issue, it is not guaranteed that the end effector is actually in the specified location. The ASLab has tackled this issue through two related aspects: implementing real-time, online motion planning with adaptive logic, and adding sensor feedback in connection with CAD for process monitoring.

Online control

To make use of the ROS software and to move away from offline control, a software pipeline has been built to connect manipulators directly to Grasshopper. Using the roslibpy software bridge [26], the CAD software can interact with ROS services and topics, and in particular with custom nodes specific to the task at hand. For example, for the brick wall assembly in Figure 3, brick poses were transferred to ROS for controlling a Kuka IIWA7, where custom logic was as follows:

1. Wait for the brick picking pose to be calibrated by hand-guiding of the robot,
2. Wait for user verification that brick is in the picking location,
3. Pick up brick,
4. Place in location at low speed, using constrained motions,
5. Repeat steps 2-5 until completion.

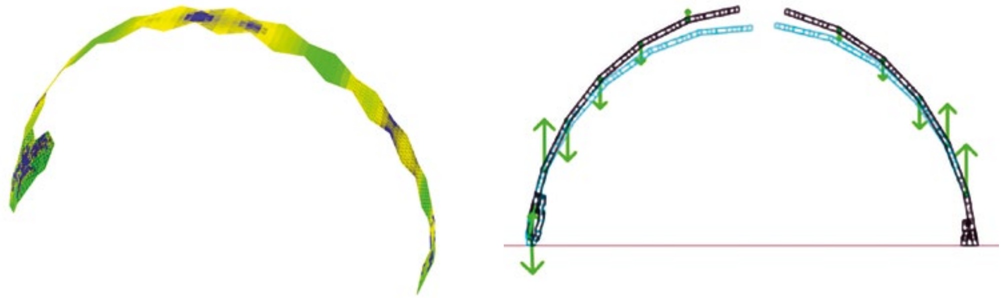

Figure 5: Structural analyses integrations within Grasshopper: (A) The R-funicularity analysis for a fully assembled arch, with blue regions showing high bending moments prone to failure; (B) CRA analysis for a partially assembled subset of the arch, showing potential deflection (blue) and interaction forces (green).

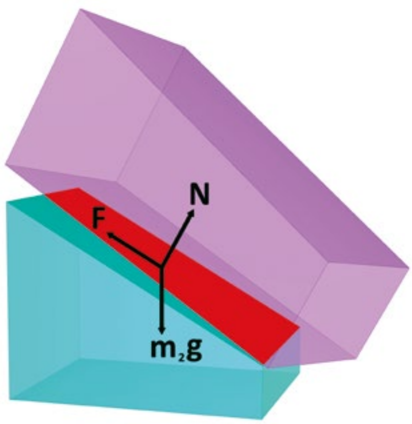

Figure 6: Base simplified rigid block equilibrium method, balancing the mass force of blocks mg, friction forces F and normal reaction forces N. Increasing number of blocks complexifies the analysis; and in CRA, virtual displacements are allowed, "activating" friction and normal forces only when there is a contact area between blocks (highlighted in red).

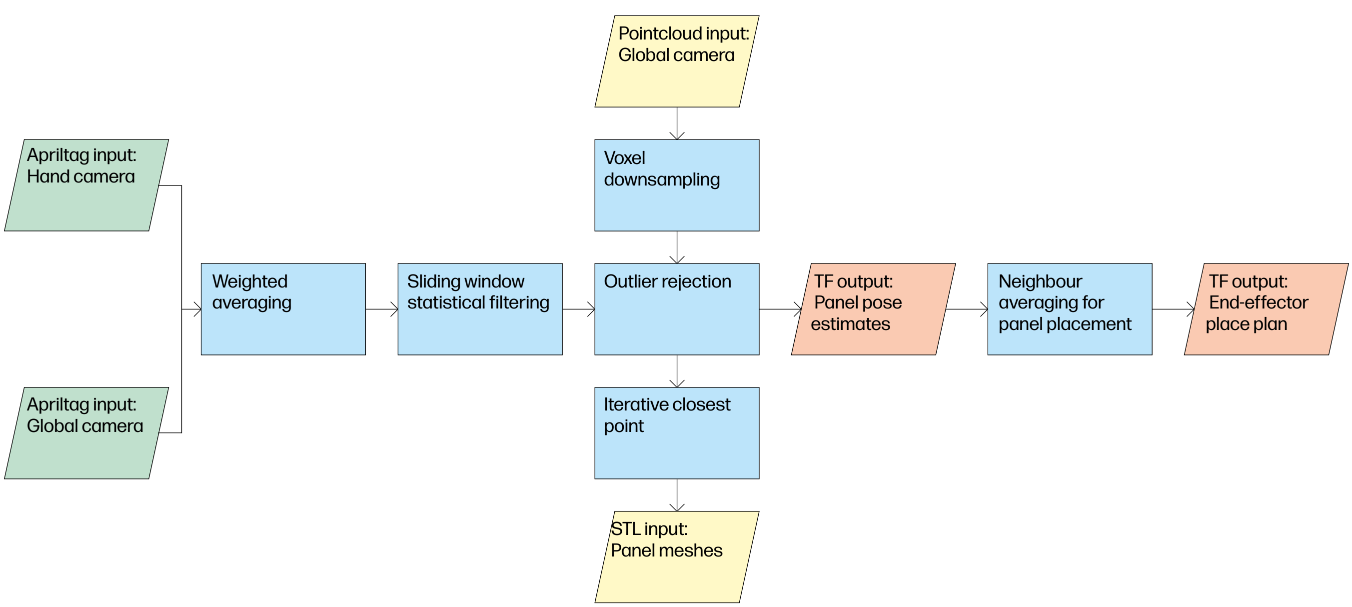

Figure 7: Sensor-based tracking used for pick/placing of panels.

Whilst for the printing simulation in Figure 1, the bridge was migrated to connect to the updated ROS2 software to run on a Fanuc CRX10iA/L arm to plan a series of motions to track a curve generated in CAD. The benefits here over offline plugin planning were that, in the case of occasional brick picking failures, the software could be told to replan and reattempt without restarting; the initial brick picking zone could be easily recalibrated during the process; and at all times, the progress of the robot could be monitored live within CAD along with a simulated representation of the assembly state. This move towards creating a manufacturing digital twin provides higher assurance of successful, robust processes.

Fiducial tags for camera feedback

A common approach to solving the issue of low accuracy in robotics is to provide a form of feedback or monitoring of the state of the environment. Through monitoring the actual state of the robot itself, it is possible to refine the state estimate provided by the robot's kinematic model. By additionally monitoring manufacturing components, they can be handled more successfully and the manufacturing state can be assessed.

Computer vision plays a key role in the current state of the art for robot process monitoring. Using machine learning (particularly neural networks) it is possible to observe using cameras, to label objects, and to estimate states. Such AI models however tend to be computationally expensive to run, dampening their utility for real-time monitoring. A faster solution is instead to encode data within objects so that it can be more easily read by a computer from an image. Fiducial markers such as AprilTags are a popular method for this. AprilTags are grid images of black and white squares which can be detected within an image, similar to a QR code [27]. Unobscured tags can be quickly detected in black and white images, with built in error metrics to prevent accidental false positives. Each tag is associated with an ID number, meaning that distinct parts can be given separate tags so that the robot control software can understand which parts are within a camera's field of view. Additionally, provided that the camera is well calibrated and the real dimensions of the tag are known a priori, the position and orientation of the tag relative to the camera can be calculated through matrix mathematics.

Initial tests were conducted in the ASLab on the use of AprilTags laser-engraved into wooden materials, to determine their effectiveness with different cameras and image resolutions, including low-cost computer webcams. Through varying light conditions and comparisons to similar black and white inkjet printed tags, a lower range of distances was reported for detection, particularly in extreme lighting conditions. It was also found that pre- and post-processing was important for tag detectability. By using masking tape on the area before laser engraving, scorch marks on white pixel regions of tags which would affect detection were reduced; while sanding could be used to clean remaining scorch marks.

Importantly, even the low-cost, readily available webcams provided high accuracy for pose estimation and tag identification on the wooden tags, as shown in Figure 8. The initial AprilTag algorithm from Olson [27] was reimplemented as part of a Grasshopper plugin, allowing real-time access to part locations for both the robot controller and the CAD model (see Figure 9B).

Such fiducial tags are of benefit here for the monitoring of parts for the digital twin model, and can help the manipulator arm to ensure correct picking and placement of parts. For manufacturing too, the use of tags as reference markers would allow the repositioning of workpieces, for example for the reorientation of printing beds in additive manufacture or for the locating of embedded components.

Point cloud data

Whilst the use of fiducial markers allows structured data to be encoded into manufacturing elements, they are restricted to use where they can a) be visible without obstruction, and b) on solid, planar surfaces. For the more general monitoring of manufacturing processes, recent work at the ASLab has approached the addition of point cloud data, observed using depth cameras.

Point cloud data gives 3D locations of points on the first surface that can be seen by depth cameras. This can be compared to as-designed mesh models for the monitoring of processes without planar surfaces, and from any angle, which makes them more applicable to a wider range of manufacturing techniques including additive manufacture. Further, point cloud data from multiple orientations can be stitched together using registration techniques to better constitute a 3D model, which is made easier in combination with fiducial tags as reference points for a moving camera frame. This was again integrated into both CAD and the robot controller to avoid collisions and improve ongoing state estimates of assembly processes. The process is a highly viable candidate for ongoing monitoring of a range of manufacture processes.

CASE STUDY USING LASER CUT CONTOUR-CRAFTED TIMBER

As a study into the various aspects explored in this chapter, an end-to-end workflow from design to fabrication to assembly was conducted. Applying reachability metrics and assembly sequencing alongside mechanics modelling,

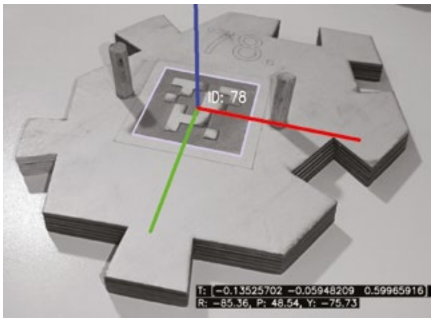

Figure 8: A laser-cut AprilTag for pose estimation on the surface of a panel, with output pose estimation data overlayed onto the image.

A B

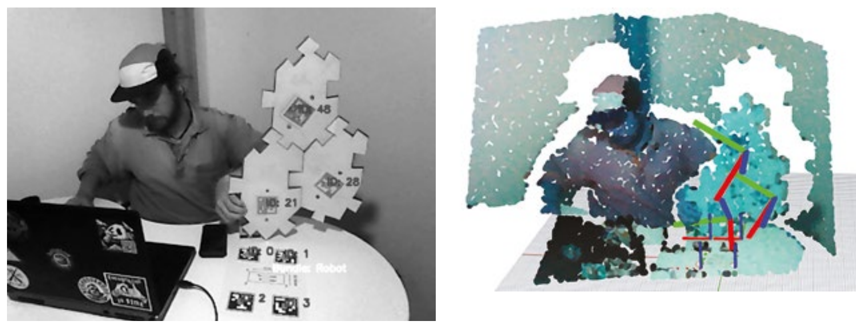

Figure 9: Direct real-time visualization of camera data within CAD software Rhino using a low resolution camera: (A) The original RGB image; (B) Visualisation of tag poses (as red/green/blue Cartesian axes markers) and point cloud data.

A B

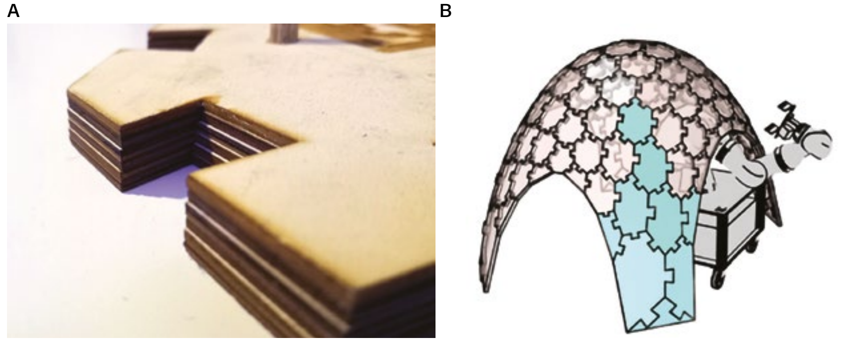

Figure 10: Stacked layers of laser cut materials allow complex geometry to form with low-cost manufacturing: (A) A sample panel, showing laminar layers; (B) A test set of panels from a designed structure, manufactured for robotic assembly.

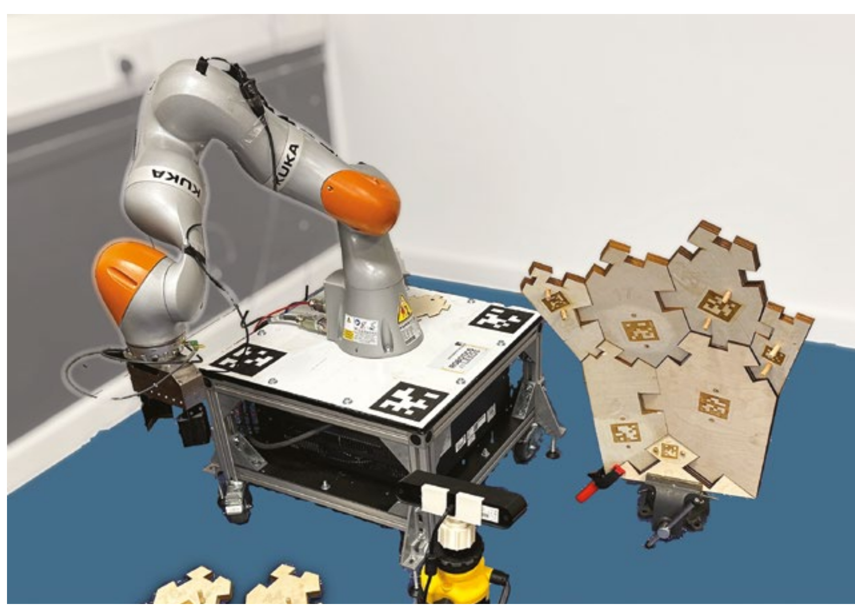

Figure 11: Successful pick and place assembly of timber panel system.

a panel structure was developed where every panel position was within the Kuka IIWA7 arm's functional workspace whilst maximising height and span (Figure 10B).

The panels were comprised of hexagonal, planar intrados and extrados, with the addition of integral dovetail joints between neighbours to withstand bending moments and support the structure through cantilevering during assembly, which the authors have previously demonstrated [21]. Due to the curvature of the structure, to maintain the planar panels, the edge surfaces require both positive and negative bevel angles. To manufacture these surfaces exactly in timber would require the use of 5-axis CNC machining rather than a less expensive Cartesian 3-axis process. As an alternative, a manufacturing method was devised using thin sheets of plywood and laser cutting. A selected subset of panels were sliced into layers at heights corresponding to the sheet material stock thickness, then border outlines were exported as vectors to instruct the laser cutting. AprilTags were additionally added to the top surfaces for rastering, whilst a pair of reference holes was cut through each panel. Once cut, the panel layers were glued and assembled by hand, with dowels inserted into the reference holes (Figure 10A). Taking quotes from CNC suppliers, the effective cost of this manufacture was reduced by a factor of 10x, and the use of thinner sheet layers showed an excellent fit with minimal post-processing between neighbouring panels, despite the stepped edges that form due to the layering process.

For robotic assembly testing, a series of AprilTags were placed around the robot base as a reference bundle. By doing this, the relative position of a camera to the robot could be found whenever the robot was within the camera's field of view. A RGB-Depth camera was placed on a tripod such that it could see both the robot base and the structure's base element (Figure 11). Due to the use of the robot base tags, the tripod could be moved freely within the environment so long as it could still see at least one robot tag and one structural tag, and provide data to the robot control software to comprehend where the next panel should be placed.

In addition to the depth cloud camera, which was calibrated to work in a range of between 1 and 3 metres, a low-cost webcam was also calibrated to work in a range of 5-30cm and attached to a known location on the manipulator's gripper, allowing better grasping of components by minimising the accuracy errors as the gripper approached parts. By combining these two input streams of AprilTag pose data, the controller gains information on both the global state of the assembly process and the local state of parts close to the end effector.

By continuous comparison of the construction to the designed structure, in particular comparing the relative pose transformations between panels, the arm was able to insert parts which it was not able to do without the process monitoring due to small errors. Particularly, deflection of the structure caused large enough changes in the structure at even this scale that the arm was unable to insert parts without the feedback AprilTag data due to the fine insertion tolerances. Planning of the arm movements was undertaken live before each form of motion (free movement, movement holding a component, slow linear motions for picking and insertion), meaning that the arm or the panel could be repositioned to get a better view or larger effective workspace. Due to this, the actual constructable workspace could have potentially much larger span than initially found in reachability analyses.

Future work on this topic will improve the digital twin aspect of the assembly by making use of the available point cloud data, to shift towards digital manufacture outside of assembly processes. For example, adaptive online planning of additive manufacturing processes could conceivably allow the generation of procedural printing paths and adaptive print speeds, augmenting the models of 3D manufacturing processes to improve print quality and size constraints.

CONCLUSIONS

A series of steps have been described for the end-to-end workflow of creating a digitally designed, manufactured and assembled panel structure. Through the development of software tools for robot workspace analysis and assembly sequencing, the designer can receive early-stage feedback to understand the feasibility of using manipulator arms for manufacturing processes. These are important factors when working with the often unintuitive kinematic capabilities of manipulators as well as to understand whether designs can be realistically assembled without potentially damaging collisions.

Structural aspects have been explored and describe the use of mechanical models for the assessment of not only the finished component, but also intermediate manufacturing stages. Such modelling of the full-process is here vital for assembly without scaffolding, and similar techniques should be implemented into complex geometry additive manufacturing processes to understand the stability of workpieces throughout the manufacturing process, whether that be through empirical models or more computationally expensive finite element methods.

The addition of sensors and online planning which is generated on-the-fly allows for dealing with non-deterministic, changing environments and aids in dealing with tolerances and calibration errors. The use of fiducial reference tags is shown to allow the movement of sensors, workpieces or robot manipulators without negatively affecting calibration, as automated calibration can be continuously reapplied to find the relative poses between the work materials and robot. In combination with point cloud data for taking 3D measurements, it should be possible to improve printing quality in manipulator assisted additive manufacture by constantly monitoring output geometry and adapting print parameters. Further, reference tagging and automated calibration shows promise for being able to work in larger span workspaces than the robot could reach on its own, through repositioning of the robot base. Ultimately, 6 degree of freedom kinematic devices like manipulator arms provide notable opportunities for the improvement of advanced manufacturing, and future research should continue to focus on moving away from offline planning in favour of augmented, feedback driven processes to generate improved end artifacts.

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TOOL-FREE CONNECTION SYSTEM FOR ROBOTIC ASSEMBLY OF LIGHTWEIGHT SHELL SYSTEMS

Emil Korkis
Ornella Iuorio

Robotic assembly of shell systems requires rethinking about how shell components are connected together. This research proposes a new standardized connection system for single curvature panelised systems. A triad connection at the vertices of a hexagonally tessellated structure has three independent variables, representing the three angles of the adjacent panels. The combinations of the different variables in a single shell structure produces hundreds of solutions where each solution is an independent connection. The connection system proposed solves this problem by having three articulating connecting fingers around a central hub. This connection system relies on a parametric environment and adapts to a variety of shell geometries and curvatures. The parameters of the design dictate the joint position and only reflect on the design of the panels.

This type of standardized connection offers flexibility in the design of the structure, as well as being suitable for repurposing and use in other projects. The connections are designed for 3D printing "in-place" to reduce assembly and post-processing. The nature of this design makes it inherently easy to adjust for robotic assembly by changing the central hub features for easier manipulation by a robotic gripper. The validity of this solution is assessed in this work through tensile testing .

INTRODUCTION

Shell membrane structures are a type of architectural and engineering form characterized by their thin, curved surfaces that efficiently carry loads primarily through in-plane membrane forces (tension and compression). These structures are inspired by natural forms such as eggshells and soap bubbles, which exhibit remarkable strength and stability despite their thin profiles.

The key feature of shell structures is their ability to distribute loads across their surface, minimizing bending and maximizing structural efficiency [1]. The distribution of forces through membrane action enables shell structures to cover large spans with substantially less material use compared to other types of structures, making them an ideal choice for lightweight and sustainable designs.

Shell structures are typically constructed from materials such as reinforced concrete, steel, aluminium, or composites, the choice of material is only restricted by the desired strength, flexibility, and aesthetic considerations. However, depending on the required performance, more sustainable materials can be used such as timber [2]. The applications of shell structures are diverse and include roofs for stadiums, auditoriums, exhibition halls, and transportation terminals.

The geometry of shell structures can take various forms, either free-form or form-found shells. These geometries are designed either using principles of mathematics, physics, or computational modelling to ensure optimal performance under varying load conditions [3]. Independently of the geometry, shells can be categorized in terms of curvature into one of two categories, single curved, and double curved surfaces. The design methodology can either produce traditional vaults such as domes, and barrel vaults, or more innovative shapes such as hyperbolic paraboloids.

Regardless of geometry, shape, and curvature, shell structures share benefits in design and construction that provides freedom of design exploration and efficient loading resistance [4]:

- Material Efficiency: The curved geometry allows for a reduction in material usage without compromising structural integrity and strength.
- Aesthetic Appeal: Shell systems produce elegant forms that are visually attractive, making them a popular choice for iconic architectural projects.
- Structural Performance: They provide excellent resistance to external forces, such as wind and seismic loads.
- Adaptability: They can be adapted to various architectural and functional requirements.

Despite their advantages, designing and constructing shells requires precise engineering, advanced computational tools, and skilled labour. The analysis of these structures often involves complex calculations, considering factors such as non-linear behaviour, buckling, and long-term material performance.

Shell structures represent a perfect blend of art and engineering, combining functionality, sustainability, and beauty. Their continued evolution is driven by advancements in materials science and computational design, opening new possibilities for innovative and efficient architectural solutions. This work specifically investigates advancing their application by enabling the robotic assembly of segmented systems.

SEGMENTED SHELL STRUCTURES

Segmented shell structures are a subset of shell constructions made up of discrete elements that are joined together to form a larger structural system. Unlike monolithic shells, segmented shells are built by assembling smaller, prefabricated, or modular components, which makes them highly versatile and suitable for a wide range of architectural and engineering applications.

Segmented shells retain many advantages of traditional shell structures, such as material efficiency and aesthetics, while addressing certain challenges related to constructability, scalability, and cost. An excellent example is the livMatS Biomimetic Shell at the FIT Freiburg Centre [5] that showcases the possibility of multidisciplinary approaches to segmented shells.

Segmented shell structures offer a versatile and efficient approach to modern construction. Their modular nature, combined with advancements in materials and computational design, allows for innovative and sustainable architectural solutions. While challenges such as joint design and structural continuity persist, ongoing technological advancements continue to expand their applications and possibilities.

Lightweight shell structures are a specialised category of thin curved surfaces that derive their strength purely from their geometry. The efficient use of materials in the design of these structures produces a structurally stable structure that can withstand multiple times its own weight.

CONNECTION SYSTEMS FOR ROBOTIC ASSEMBLY

Most structures require a way to connect different elements of the design, regardless of the building method and the materials used. However, unlike traditional building methods, robotic assisted construction introduces a different challenge to the design phase of a connection system. While traditional connections like beam-column connections are designed following certain conventions, standards and experience, instead systems compatible with robotic assembly can be different. Such systems, indeed, need to follow different sets of rules, as the process of assembly has to be handled by a robotic manipulator, and the process must be solvable by the used robotic system.

PROPOSAL OF CONNECTIONS

Segmented structures typically require a larger number of connections at the joint locations determined by the design. For example, a reinforced concrete shell structure typically has connection points at the location it links to the substructure, where a segmented wooden shell structure requires connections between the elements of the superstructure as well as linkage to the substructure.

Connection systems for the substructure vary and depend mainly on the geometry of the elements and the material used. Other considerations include the self-weight of the structure, expected loading conditions, and construction method.

Considering the case in figure 1, the ECHO shell structure made of segmented 6mm thick plywood panels, individually planar and hexagonal in shape, developed and presented in Barcelona in 2019 [6]. The hexagonal shape of the panels introduces intersection vertices shared between each three adjacent panels. There are multiple ways to connect the panels while maintaining the continuity of the shell, such as edge-to-edge connections and vertex connections. Both solutions are possible and valid but have different characteristics. Edge-to-edge connections are those connecting two adjacent panels and are the most common typology used for this type of segmented structures. Although not particularly complex, edge-to-edge connections can be more difficult to implement in a system for robotic assembly (RA) . The other type is vertex connections, a less common method of connection due to the added complexity of design, however, it has its advantages when it comes to RA friendly designs.

While edge-to-edge connections join two panels on two different planes, Vertex connections join three panels on three separate planes. This added complexity can be circumvented by designing the connection in a parametric environment that, although more time consuming, it solves the problem of having to directly design many ad-hoc connections at slightly different angles for each vertex.

The shell structure shown in figure 1 was parametrically designed for manual assembly. The 144 connections join 94 panels using two-part connections attached together with a central screw and to the panels with pegs and slots (Figure 2). The 3D printed connections proved to be reliable and withstood several assembly/disassembly cycles, however, the friction fit nature of this connection makes it incompatible with any RA project.

In order to avoid the difficult task of robotic assembly of a friction fit connection, another type of connection was developed (Figure 3). A multiple part connection with moving parts that secure the panels together with a 70-degree twist of the connection shaft. This bulky solution proved to be very complex and time consuming to design, refine, and manufacture. In addition, it continued to be an ad-hoc solution, that needed to be designed for a specific set of 3 panels.

Following the previous design, an attempt to simplify the connection as much as possible while maintaining RA friendly design features resulted in a fixed connection (with no moving parts) as shown in figure 4. This attempt reduced the bulk of the connection dramatically and maintain a robotic assembly friendly design. However, even this carried over the problem of being an ad-hoc connection.

DESIGN OF A STANDARDIZED CONNECTION

Designing any type of connection requires a balance between ease of manufacturing, cost, size, strength, and standardization across the project. For example, Increasing the yielding point of the connection or one of its parts under a specific load, beyond the requirements of the project, is pointless if detrimental to other requirements. With this in mind, a new typology of connections was designed (Figure 5), focusing on standardization of the connection across the entire design.

The new connection consists of a central hub and three articulating arms. The arms rotate independently around three separate axes intersecting at a point at the centre of the hub, this point is the vertex of three adjacent panels. The 20-degree rotation of the arms, shown in figure 6, accommodates any panel angle combinations for the whole design to create a standardized design.

Each arm has a protrusion at the end, which acts as a finger, to be inserted into a slot, located at each corner of the corresponding panel. The location of the slot on the panel changes depending on the angle, however, considering the panels are already a parametrically created element of the design, the added complexity is very limited when compared to the avoided complexity of an ad-hoc connection. The shift of complexity from the design of the connection to the already parametric panels opens the possibility for further simplification of the design, with exploration in the use of different materials, and the use of advanced manufacturing processes.

MATERIALS AND MANUFACTURING

The choice of materials and manufacturing methods are interlinked, and both depend heavily on the function of the structure, expected loading scenarios, structural considerations, and sustainability. A model of a shell structure, for example, for indoors use in showrooms is not subjected to live loads, wind loads, or snow loads but need to be structurally sound. Structural stability, however, is a requirement for all projects regardless of the intended use. In the previous project, the echo shell was designed to be transportable with multiple assembly/disassembly cycles in mind, and Poplar plywood was the material of choice for its thin and lightweight properties. Based on the material choice, many manufacturing methods can be used, laser cutting was chosen, being the most accessible and fastest for that specific project. The manufacturing methods available to create the connections are much more limited, due to the small details in the connections and tight required tolerances. 3D printing, while not the fastest manufacturing method, proved to be versatile for scaled down models of any size.

Polylactic Acid or PLA was chosen for the Echo shell and continues to be used for 3D printing of connection systems due to its good mechanical properties and the ability to withstand relatively high temperatures. PLA is a biodegradable material that is most commonly used in Filament Deposit Manufacturing (FDM). PLA is typically

Figure 1: The ECHO Shell: A segmented lightweight shell structure.

Figure 2: Friction fit connection system for the ECHO shell.

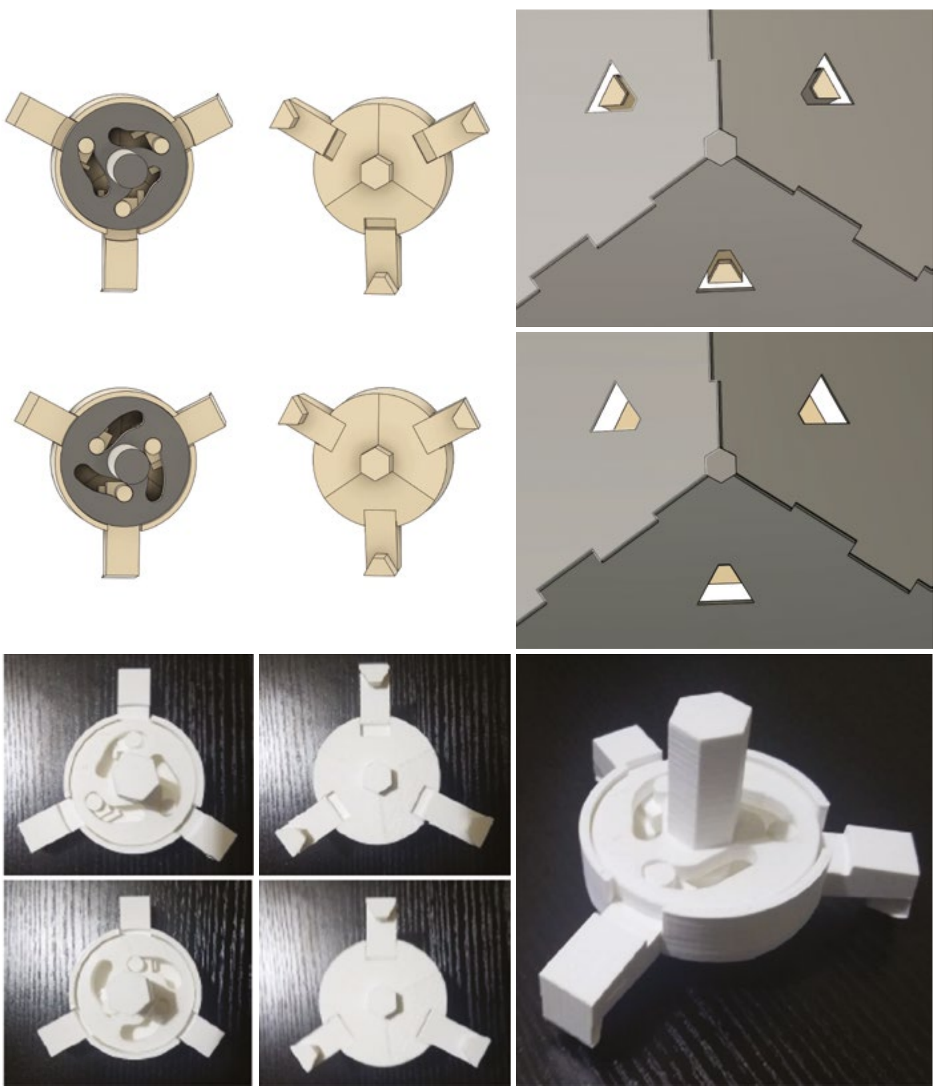

Figure 3: A non-standardized connection system for robotic assembly of shells with moving parts.

Figure 4: Ad-hoc Robotic assembly connection.

Figure 5: A standardized connection proposed for robotic assembly of shell systems.

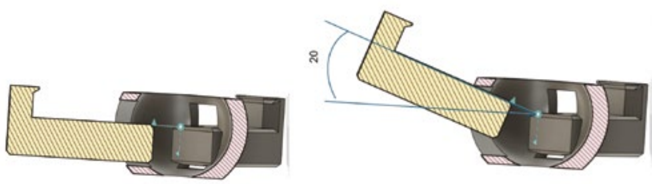

Figure 6: A cross section showing the limits of the movement of a single arm of the connection.

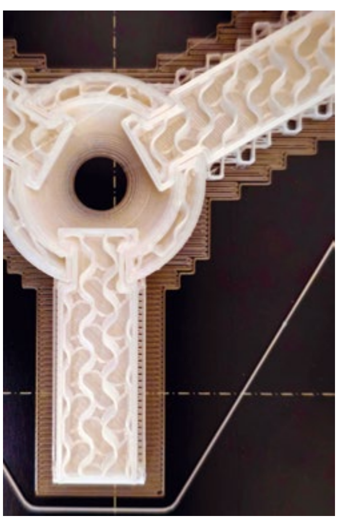

Figure 7: A top view of the connection showing the infill pattern.

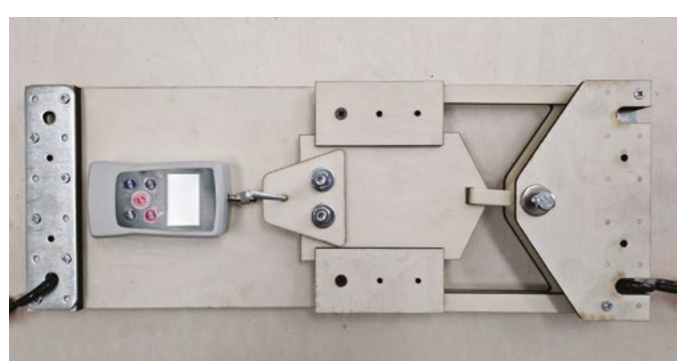

Figure 8: The destructive connection testing apparatus.

manufactured using fermented plant starch, a renewable source, which makes it accessible and more sustainable than other comparable materials.

PLA is quite extensively tested for its interlayer adhesion, hardness, moisture absorption and various mechanical properties that make it ideal for fast and reliable prototyping. PLA 3D printed parts testing is also covered by multiple standards as reported in Table 1 [7].

Table 1: Material properties of the used Polylactic Acid (PLA) filament

Property	Typical Value	Method
Density [g/cm3]	1.24	ISO 1183
Moisture Absorption in 24 hours [%]	0.13	Prusa Polymers
Tensile Yield Strength for Filament [MPa]	57 ± 1	ISO 527
Hardness - Shore D	81	Prusa Polymers
Interlayer Adhesion [MPa]	17 ± 3	Prusa Polymers

The standardized connection is manufactured using an FDM 3D printer with PLA filament. A full connection is printed in "in-place" which refers to the printing of the full connection including the moving parts (arms) at the same time.

The tolerances built in the design and the accuracy of the FDM printer used makes printing in-place possible. This reduces the parts required to build the connection, and eliminates the time required for assembly. A full connection is 3D printed in one hour with minimal supports on the build plate only, which minimizes post processing to removing the supports in a few seconds.

The connection is not printed as a solid part, rather with two perimeter walls. The remaining volume of the part is occupied with an infill from the same material with a volumetric percentage of 15% and a gyroid infill pattern. The infill pattern and density remain constant for all connections tested to limit the number of variables. Although the infill pattern is shown to have an effect on the mechanical properties, this effect is more noticeable at higher infill densities [8]. Figure 7 shows the connection while being printed on the bed.

TESTING

Considering the manufacturing process and the materials used for this connection, finite element analysis should not substitute physical testing when possible. It is possible, however, in future studies to construct an FEA model that closely represents the real connection using the results of this study combined with further testing on infill patterns and percentage.

In order to better understand the failure mode and yielding stress of the panel-connection system, a testing apparatus was custom made to accommodate a connection and a freely moving section of a panel with the same coupling features found on a regular panel (Figure 8).

The apparatus is composed of two moving sections. A first section consists of a push-pull force gauge with 500N capacity, attached securely to a rigid base. The force gauge's load cell is connected to the panel with a freely rotating pin to eliminate sideway forces and reduce friction. The panel moves on a set of rails with 1-degree of freedom, in the direction of the force. The other part of the apparatus consists of a place holder for the connection that allows a pin to go through the connection's hub. The two parts mates each other using two rails that allow 1-degree of freedom in the direction of the applied force.

Each section has two points to allow the attachment of the force applying pulleys. The force applied is always a pulling force, that is applied until failure. The incremental increase of the pulling force is transferred completely through the metal parts of the apparatus and is transferred to the connection-panel coupling surfaces through the panel and the hub of the connection.

Two connections geometries for the same connection typology were tested, and the highest force registered on the force gauge was recorded. The following table summarizes the properties of Type A and Type C connections.

Table 2: The properties of the two geometries of connection tested (Type A and type C)

Connection Geometry	Arm Length (mm)	Arm Width	Arm Height	Infill (%)	No. of perim.	No. of samp.
Type A	30	12	10	15%	2	9
Type C	35	10	10	15%	2	9

Figure 9 shows the test results. The results recorded from testing for each type were averaged and the standard deviation was calculated. The samples with results higher or lower than the average by more than one standard deviation were discarded. Therefore, samples number 1 and 8 were removed for connection Type A and samples number 1 and 2 were removed for connection Type C, for being more that 1 standard deviation away from the average. The new averages were calculated based on the 7 remaining samples for each type (Figure 10).

In advance of testing, the failure points of the connection, under tension and compression, were expected to be the mating surfaces between the hub and the arm, as well as the ends of the arms that connect to the panels, as marked in red in Figure 11.

Testing has shown that the failure point (Figure 12) is consistently the fingers at the end of the arms where the loads shear the finger at a 45° angle almost in all cases of the tested connection. The failure is a combination of layer separation and cross-layer shear, which is an indication of good layer adhesion at that point.

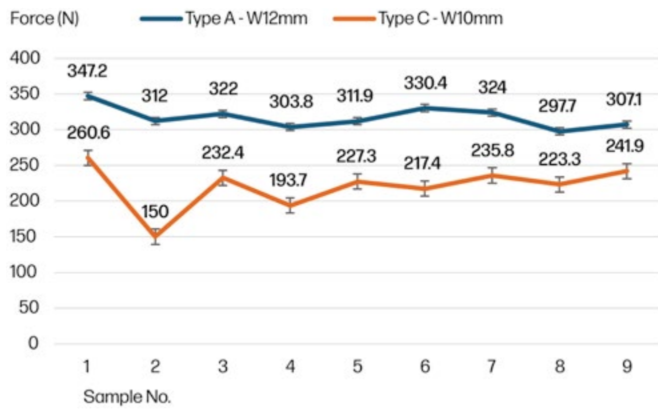

Figure 9: The results of destructive testing of the connections in Newtons.

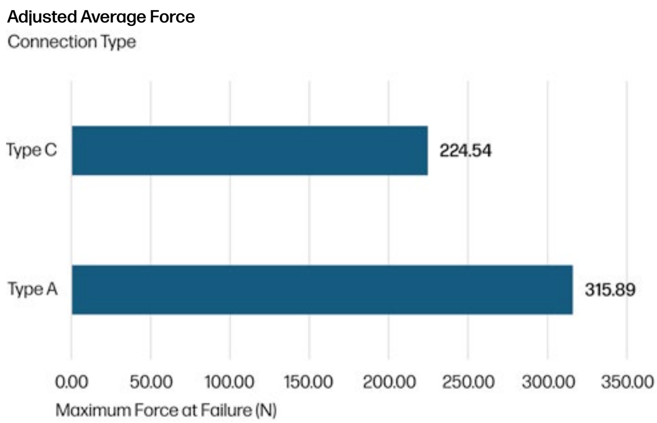

Figure 10: The adjusted average of the force required to break the two geometries of the connection tested.

Figure 11: The potential failure points of the connection.

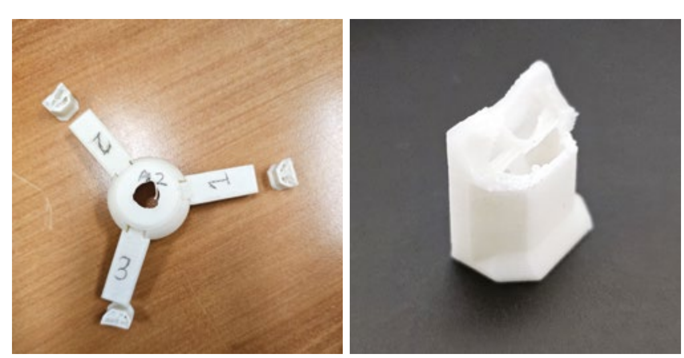

Figure 12: An image of the sample after testing showing the full connection (left) and the failure points at the fingers (right).

Based on the testing results, it was clear that Type A connections were 40% stronger than Type B connections. This is due to the increase in the width of the arm at the failure location. However, it is unclear whether the relationship between the width of the section and the strength is linear or not. Further testing with a wider range of samples is required. It is also unclear how the number of perimeters and the infill percentage affect the strength of the part in this location and whether the failure mode changes when changing these parameters.

CONCLUSION

Automating constructions is a clear trend that is starting to see initial developments, with few real applications. This study is centred on automating the assembly of discrete lightweight shell systems. The intent is twofold, developing assembly processes that can be realized with robotic manipulation and developing tools that facilitate that. Therefore, a series of connections have been proposed and prototyped with additive manufacturing. Among them, in particular, a standardized connection, to be used for connecting the vertices of segmented panels composing a single curvature surface, has proved to be easy to manufacture with very little post-processing. Mechanical testing has shown that the weakest point of the chosen type of connection was able to withstand a relatively high force. In the future, to further understand the application of AM for fast reliable prototyping, it is perceived important to investigate the effects of other variables, such as infill percentage, pattern and number of perimeter walls, on the mechanical properties of AM manufactured connections. In conclusion, this type of connection can be considered a first step towards a fully automated assembly of lightweight shells, that cuts down the time needed to assemble the structure with minimal intervention and minimal supports-structures.

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AUTOMATING CIRCULARITY IN TIMBER CONSTRUCTION THROUGH COLLABORATIVE CYBER-PHYSICAL RECONFIGURATION

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Roberto Naboni

As the construction sector moves toward circularity, reconfigurable timber systems are gaining prominence for their potential to enable material reuse, adaptability, and extended carbon storage. This article introduces *ReconWood*—a cyber-physical construction framework that integrates computational design, robotic fabrication, human-robot collaboration, and mixed reality to operationalise circularity in timber architecture. By treating timber reconfiguration as an additive, iterative process, ReconWood supports the precise assembly and disassembly of modular components designed for reuse. The system incorporates voxel-based generative design, digital twins, and material passports to maintain continuity between physical elements and their lifecycle data, ensuring traceability and reuse across multiple construction cycles. Robotic mass production and mass customisation enable scalable fabrication, while collaborative assembly processes—augmented by real-time sensing and extended reality—facilitate adaptive decision-making and on-site flexibility. By embedding intelligence across digital and physical domains, ReconWood positions automation not as a marginal enhancement but as the foundational infrastructure for implementing circular construction at scale.

INTRODUCTION

In contemporary architecture, the resurgence of wood is not merely aesthetic or nostalgic but is fundamentally driven by its structural efficiency, regenerative properties, and capacity for carbon sequestration. While forests serve as Earth's largest terrestrial carbon sinks, timber buildings offer a unique opportunity to extend this function beyond the lifespan of trees. When timber structures are designed for longevity, adaptability, and reuse, the built environment can be reimagined as a globally distributed, dynamic system of long-term carbon storage that evolves in response to changing conditions. Material circulation is essential to realise this vision.

This research advances the thesis that automation is not a peripheral enhancement but a foundational enabler of circularity. It does so by embedding data continuity, operational reversibility, and adaptive decision-making across the entire material lifecycle.

To achieve this, the concept of material circulation must be expanded beyond physical flows. It is essential to establish robust data flows accompanying materials, encompassing information such as composition, origin, mechanical properties, design specifications, and lifecycle history. These data must remain continuously accessible to enable effective reuse. In this context, automating the planning and coordination of construction processes while maintaining real-time awareness of material conditions and flows becomes critically important. Automation enhances the scalability of circular construction by providing tools that bridge tacit, locally embedded material knowledge with the global information infrastructures through which the industry increasingly operates.

The vision of automating circularity promotes systemic change across scales. It involves reducing fragmentation within construction value chains through integrated digital workflows, improving interoperability among stakeholders through open-access tools and shared data environments, and enhancing transparency through real-time data acquisition and exchange. At its core, this approach fosters a cultural shift in which buildings are conceived to balance planetary health with temporary social, political, and economic requirements.

Contemporary digital and automation technologies make it possible to design buildings as documented and disassemblable material banks, from which materials may be recovered and reused after each lifecycle [1,2]. Robotic fabrication and assembly provide precise, repeatable, and efficient manufacturing processes, reducing construction waste and preserving the structural integrity of timber elements [3]. Additionally, the integration of Industry 4.0 (I4.0) technologies—including the Internet of Things (IoT), extended realities (XR), and human-robot collaboration—enhances the adaptability of construction processes under variable site conditions and unstructured environments [4–7]. In such contexts, data-driven control of fabrication and construction activities supports future disassembly and reuse. Likewise, data-informed design and engineering embed circularity at the inception of the construction process.

The use of digital twins further enables continuous tracking of a building's lifecycle, supporting structural adaptation and optimising reuse scenarios. AI-based design platforms can evaluate and propose structural configurations based on existing material inventories, facilitating a shift from new material production to intelligent, availability-driven reuse [8,9]. Material passports (MPs), underpinned by blockchain, IoT sensing, and digital tagging, support traceability and lifecycle management by maintaining a transparent record of each component's provenance, treatment, and mechanical properties [10–12]. These systems ensure that even as components are disassembled and reassigned, their value and usability are preserved.

Recognising information as the integrative element between digital tools and physical processes, SDU CREATE's research explores how generative, stress-informed design, collaborative human-robot construction, mixed reality (MR), and cyber-physical systems can together advance circular timber architecture [13–16]. In this context, we define automating circularity as a systemic framework for operationalising reuse, adaptability, and lifecycle management within the built environment. Crucially, this approach is not limited to improving efficiency; it enables circularity to function as a scalable and actionable paradigm. Without automation, circular construction remains confined to artisanal or small-scale experimentation, hindered by data discontinuities and the unpredictability of manual processes. Automation, therefore, is not a secondary enhancement but the operational foundation and infrastructural logic that renders circularity technically viable and strategically applicable across spatial, temporal, and structural contexts.

RECONWOOD: AUTOMATING CIRCULARITY THROUGH DATA-DRIVEN RECONFIGURABLE CONSTRUCTION

The ReconWood research framework advances the proposition that technologies typically associated with automation—robotic assembly, computational design, digital sensing, and real-time data integration—must be reinterpreted as enablers of circular logic. It introduces the reconfigurable design and construction of modular timber frame systems composed of digitally traceable elements as a scalable solution for a dynamic built environment capable of transformation, adaptation, and sustained carbon sequestration across multiple lifecycles. The framework involves closed-loop communication between computational design environment, materials and collaborative human-robot construction processes with real-time data acquisition to ensure the traceability, reversibility, and reusability of building components.

The system is conceived through data-driven generative design supporting the optimisation of spatial and structural performance while anticipating future disassembly. Robotic fabrication technologies are used to produce and assemble the timber elements into reconfigurable frames ensuring precision and consistency while reducing damage during installation and enabling clean deconstruction. In contrast to the conventional construction where material histories are fragmented, component conditions remain undocumented, and disassembly often results in loss or damage, the ReconWood construction parts integrate embedded material identifiers and digital twins maintaining continuity between physical components and their lifecycle data, and ensuring that each element's history, condition, and reuse potential remain accessible. Together, these technologies form a cyber-physical infrastructure through which materials can circulate within and across building projects, rendering circularity a designable and executable process rather than a conceptual aspiration.

In this sense, the ReconWood concept builds upon and extends the historic paradigms of reconfigurable "programmed architecture" and cybernetics [17-19] to pursue adaptable, resource-efficient, and user-responsive architectural environment. The system of stress-informed timber structures, optimised for robotic assembly and disassembly, has evolved through a series of research prototypes (Fig. 1). These are composed of layered assemblies of modular construction parts connected through semi-interlocking, cross-shaped shear keys secured with reversible steel fasteners. Each part is individually identified via QR code imprints, which link the physical element to its digital twin, allowing for uninterrupted tracking and tracing across uses.

The multi-resolution timber frames reveal the underlying computational voxel-based design methods, used to translate structural conditions and material constraints into modular tectonic rules. This approach enables rapid iteration of designs that satisfy both performance criteria and reusability demands. By embedding digital intelligence within modular timber structures, ReconWood reconceives the building not as a fixed form but as a dynamic and evolving system.

Reversible timber tectonics and construction kit of parts

The reversible ReconWood construction system is based on a kit of parts arranged in layered orthogonal frames with varying material densities. The kit of parts (Fig.2), produced out of laminated veneer lumber (LVL), is available in three cross-sectional heights and a range of modular lengths, allowing for scalability and customisation in different architectural applications. The basic modular unit is represented by a single cross-shaped shear key. The shear keys are designed to enhance the shear capacity of the bolted joints and facilitate assembly and disassembly by a single robot arm [20,21]. During assembly, the male and female sides of the joints interlock, preventing displacement and rotations of the parts and ensuring precise positioning.

LVL was chosen as a material due to its high strength, dimensional stability, and resilience to environmental fluctuations. These properties ensure that modular parts maintain their precision and integrity over multiple reconfigurations. Furthermore, by replacing commonly used wood screws and nails with pre-drilled bolt-nut fasteners, localised material damages are prevented and the ease of disassembly is ensured. Such features enhance the durability of each element, supporting an extended lifecycle within a circular construction framework.

Additionally, the integrated QR codes enable seamless material tracking and data-informed construction planning. The QR codes link the physical parts to cloud-hosted databases that are accessible to different tools, processes, and stakeholders, fostering an adaptive material ecosystem.

The construction kit is fabricated and prepared for its final use through a two-stage procedure (Fig.3). The first one involves the robotic *mass production* of generic reconfigurable parts through subtractive manufacturing of shear keys. These parts can be virtually infinitely reused and continuously reconfigured with no additional processing or interventions. This process currently relies on single-robot work. However, it can be industrially scaled and parallelised using multi-spindle setups, enabling the rapid production of large numbers of shear keys within minutes. Featuring high-speed production, high precision and repeatability, this process is fundamental for achieving a consistent assembly process and low tolerances among numerous construction parts. In this stage, a substantial stock of pre-fabricated beams is generated and made available for further customisation in response to the specific design goals.

On the other hand, some construction parts require additional fabrication of design-specific features and are subject to the robotic *mass customisation* process. This mostly includes the generation of additional lateral holes on the parts of the higher cross-section to accommodate specific joining needs. The combination of these two processes leverages the benefits of tailored design, offering flexibility and adaptation alongside the efficiencies and sustainability of standardisation and mass production.

Automating Design: Stress-driven generative design of multi-resolution timber framing

ReconWood leverages voxel-based generative design to define multi-resolution structural timber frames optimised for both load distribution and material reuse. The voxel-based workflow is driven by a scalar field containing performance criteria such as structural stability, spatial functionality, and environmental conditions. In response to this field, an iterative computational massing process is performed, selectively removing or preserving material (voxels) while ensuring structural stability. This rapid volumetric shaping enables high flexibility in spatial exploration during early design stages. Once a design option is selected, the resulting voxelised grid is translated into a light-frame structure with varying densities based on spatial and structural parameters. In particular, voxel attributes such as orientation, neighbour dependencies and internal stresses are analysed to determine construction rules. This translation process converts abstract voxelised forms into materialised modular units, the *maxels*, with specific tectonic properties (Fig.4). The distribution of varying maxel resolutions is iteratively adjusted based on feedback from Finite Element Model (FEM) and satisfying design solutions are achieved through a multi-criteria optimisation process, aiming to reduce the amount of employed material while satisfying load-bearing requirements. This allows for efficient material allocation and an adaptive framing strategy that responds dynamically to design constraints.

The voxel-maxel methodology governs the organisation of modular timber parts in two types of structures, *horizontal* and *vertical* (Fig.5), with their corresponding construction rules. The horizontal ReconWood slabs [22]

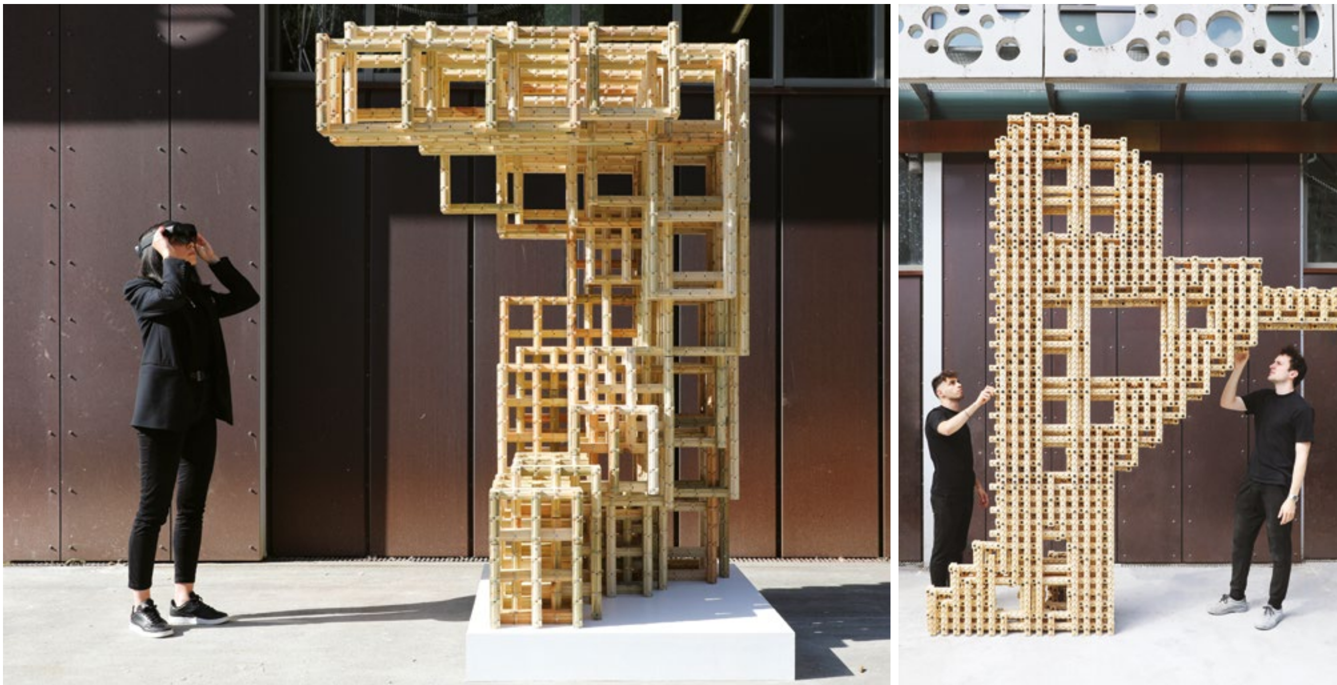

Figure 1: Incremental ReconWood construction prototypes:
a) ReconProto 01, b) ReconProto 02, c) ReconWood wall.

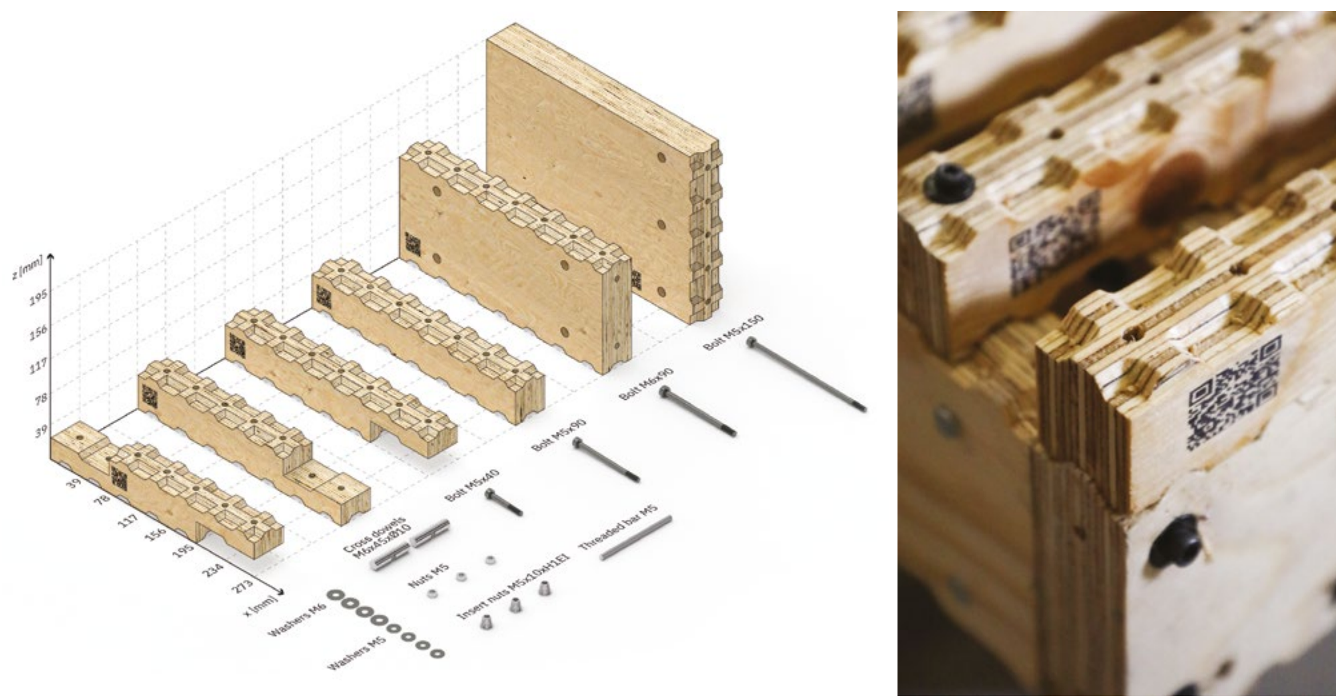

Figure 2: a) ReconWood modular construction kit; b) A close-up view of the construction parts with QR codes.

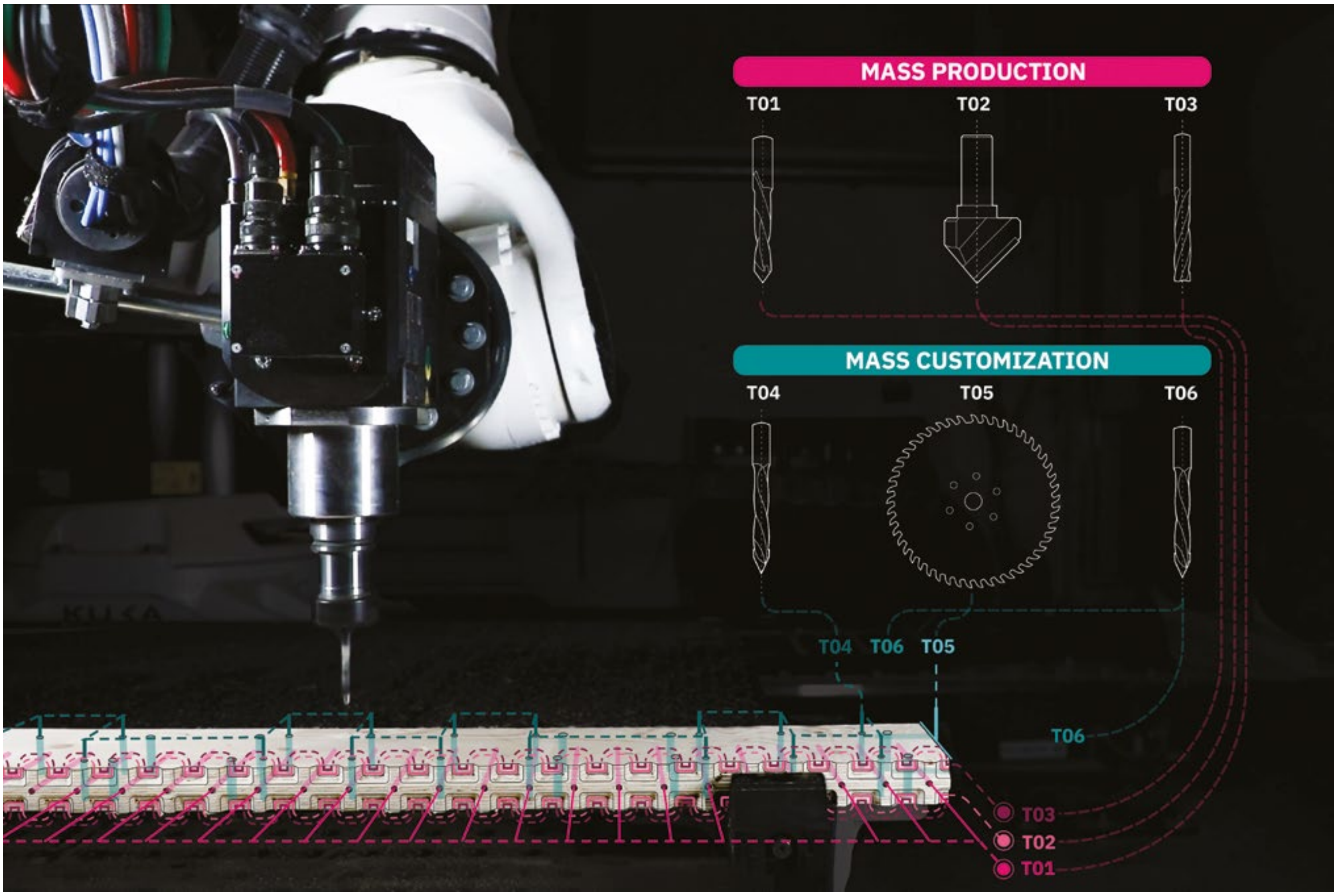

Figure 3: A two-step robotic fabrication of the construction parts.

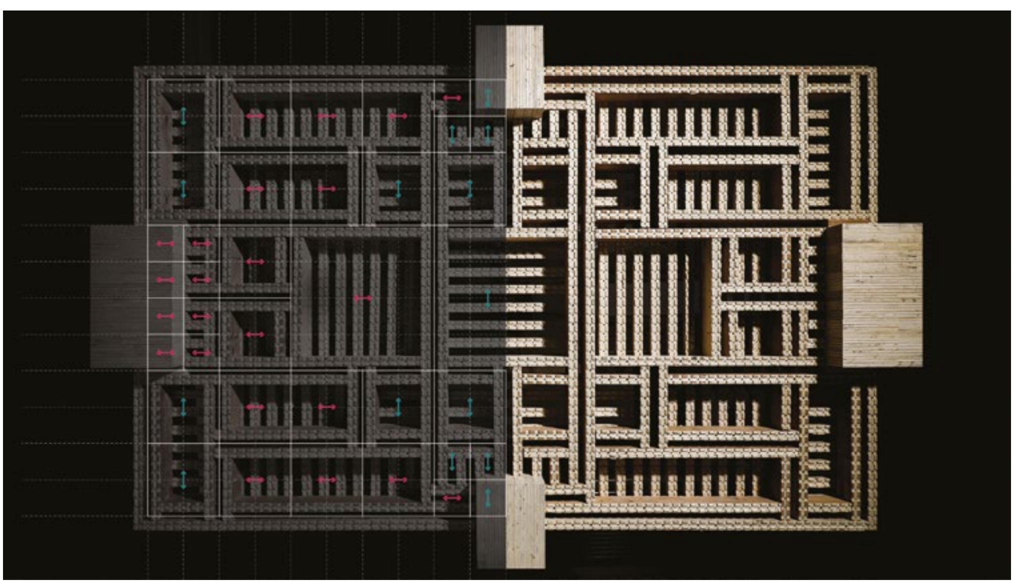
Figure 4: A bottom view of the ReconWood Slab structure highlighting the stress-driven computational design process used to generate it.

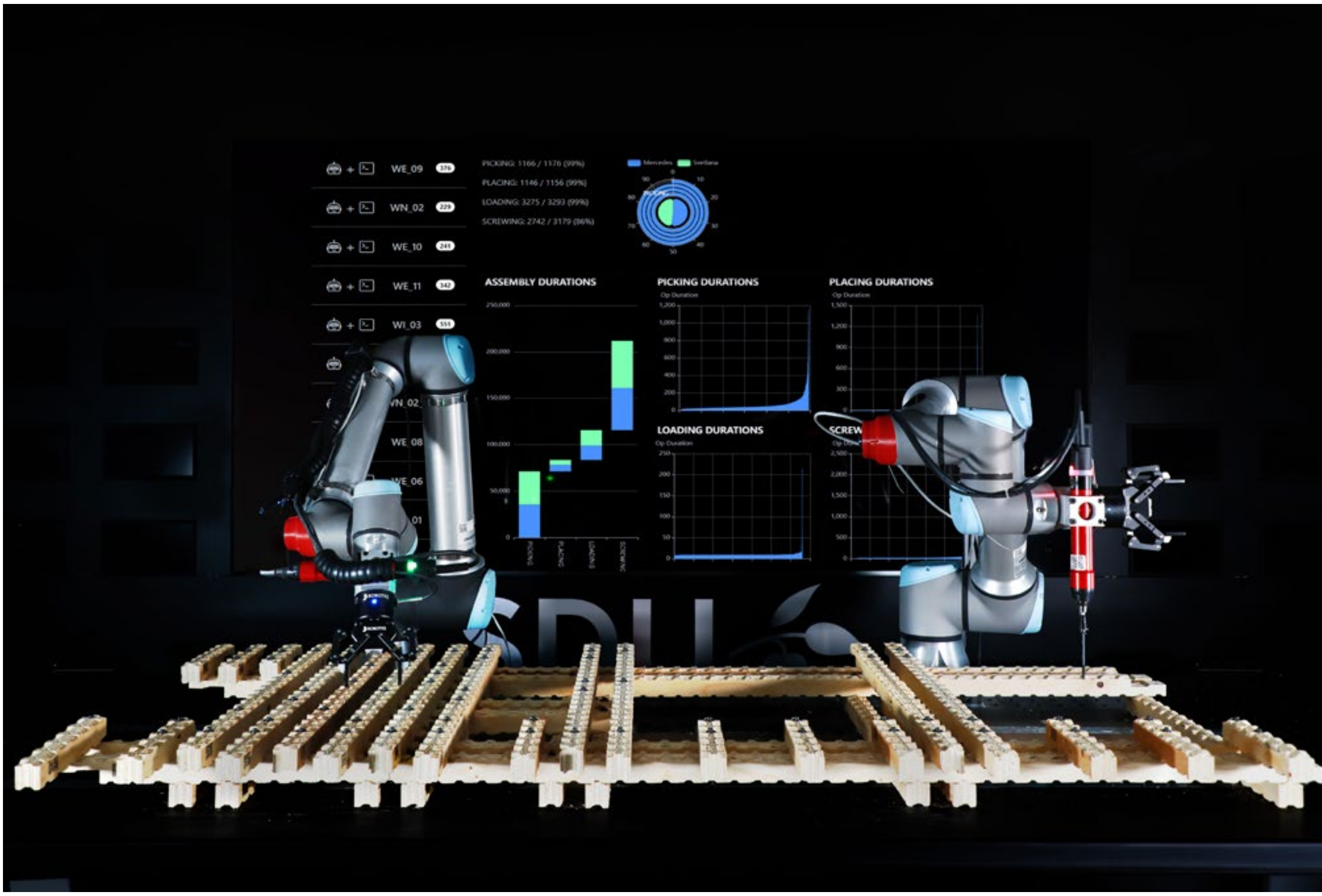

Figure 5: Cyber-physical collaborative robotic assembly of ReconWood structures.

Figure 6: Cyber-physical collaborative assembly of ReconWood structures aided by Mixed Reality.

consist of a double-layer system, including primary and secondary beams. The primary beams follow discretised Principal stresses in their orientation and density. They are characterised by higher cross-sections and in-plane connections in the form of double-bolted butt joints to increase bending moment capacity. The secondary beams with lower cross-sections are bolted on top of the primary beams, serving as additional structural stiffeners. The vertical structures, on the other hand, are characterised by a multi-layer system of parts with the same cross-sections, interconnected perpendicularly at different layers to form closed frames of various densities. The technological features of the system reflect the underlying computational principles through which they were conceived, driven by the functional and structural requirements they should serve. The data-driven material allocation and control herein introduced allow for an informed reconfigurability and reuse in future material life cycles.

Automating Assembly: Collaborative cyber-physical assembly as an enabler of material reuse

The assembly of ReconWood structures is carried out layer by layer, distributing the modular parts into controlled material layouts. This process resembles the production of functionally graded structures with additive manufacturing while preserving the reversibility and economy of mass-produced parts. It is based on the collaborative efforts of two UR10e robots, handling placement and fastening tasks with real-time sensing (Fig.6), and human operators wearing MR headsets, overseeing and intervening in the process when necessary (Fig.7). Additionally, the integration of MR allows humans to track materials and interact with their digital twins in real time, accessing design specifications, structural data, and historical usage records. Such sociotechnical collaboration, where humans and robots "see" and interact with the same datasets in a shared physical space, enhances flexibility in decision-making and error mitigation during the assembly and improves construction's adaptability to varying unknown conditions while preserving precision, efficiency, and information integrity.

Digital and physical processes, tools and operating agents communicate via closed-loop cyber-physical dataflows to ensure continuous material data acquisition, processing and exchange. The acquired assembly data is highlighted on the ReconWood website, providing insights into the most relevant performance indications. This digital-material integration establishes a scalable framework for circular construction, where materials are continuously repurposed without loss of structural integrity, reinforcing a sustainable and intelligent approach to timber architecture.

CONCLUSION: TOWARD CIRCULAR AUTOMATION IN TIMBER CONSTRUCTION

The architectural vision of ReconWood shifts the paradigm of material use, extending the lifespan of timber components beyond a single building cycle and establishing a regenerative framework. The research introduces reconfigurability, combined with digital material tracking and adaptive assembly strategies, as a way to reduce material waste, extend carbon storage and achieve architectural flexibility, preventing the need for building demolition.

The potential of automation in circular timber construction lies in its capacity to create a continuous feedback loop between design, fabrication, and assembly, allowing timber elements to be strategically allocated, reconfigured, and repurposed with minimal intervention. This approach fosters a new material economy where digital intelligence embedded in construction components enables informed reuse decisions, ensuring that each timber element retains its value across multiple life cycles.

Beyond its technical implications, the system presents a broader vision for the future of architecture—one in which buildings are no longer static entities but dynamic, reconfigurable systems capable of evolving in response to changing needs. The convergence of automated material tracking, robotic assembly, and human-machine collaboration facilitates an adaptive built environment, where architecture is conceived as an ongoing process rather than a finite product. The interplay of physical and digital data streams within the cyber-physical construction framework ensures that every assembly, disassembly, and transformation contributes to a long-term circular strategy, redefining the relationship between design and material sustainability.

For automated circular timber construction to be widely adopted, several challenges must be addressed. Standardisation of reconfigurable timber components and their corresponding digital tracking systems will be crucial in ensuring interoperability across different projects and scales. The integration of AI-driven predictive analytics could further refine material lifecycle management, enabling structures to anticipate and adapt to environmental and load conditions autonomously. Additionally, advancements in policy frameworks and industry regulations will play a pivotal role in fostering the transition towards a construction economy where materials are not simply consumed but continuously repurposed within a closed-loop system.

By positioning timber construction within the logic of cyber-physical automation, ReconWood advances the discourse on sustainability beyond mere resource conservation, advocating for an architecture that is intelligent, responsive, and inherently circular. The potential to scale such methods to larger architectural typologies, from housing to infrastructure, suggests that automation will be instrumental in shaping a future where timber buildings function as dynamic material reservoirs rather than as endpoints of a linear construction process, fundamentally redefining how the built environment is conceived, constructed, and perpetually renewed.

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Figure 7: ReconWood architectural demonstrator showcasing the integration of wall and slab structures.

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TECHNOLOGY TRANSFER FROM AUTOMOTIVE TO ARCHITECTURE: INTEGRATING WAAM AND GRC WITHIN DFMA FOR COMPLEX DESIGN STRATEGIES

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Architectural and construction practices have evolved in response to shifting societal, cultural, technological, material, and economic conditions. Within the context of climate change, the introduction of Design for Manufacturing and Assembly (DfMA) strategies in the AEC (Architecture, Engineering and Construction) sector has shown its potential to support more sustainable building practices. However, the emphasis on performative aspects leads to oversimplifications of construction processes, while the application of guidelines and frameworks that prioritise modularity and prefabrication can compromise design ambition and geometric complexity.

This study aims to restore the centrality of design by integrating DfMA principles with cutting-edge technologies to expand the boundaries imposed by conventional prefabrication. In doing so, the research explores how to leverage the concept of technology transfer from the automotive industry, which is driven by highly competitive market dynamics and can embrace new technologies rapidly. The implementation of cross-functional management tools capable of aligning design objectives and functional performance, combined with Wire Arc Additive Manufacturing (WAAM) technologies, can guarantee formal freedom and address sustainability by reducing the weight of the components and emissions during production. In parallel, the study examines the use of Glass Reinforced Concrete (GRC), a material known for its versatility, strength, and capability to create complex geometries. Building on these technologies, we propose a robotic automated manufacturing process to streamline the production stages of a façade component.

INTRODUCTION

In the Architecture, Engineering, and Construction (AEC) sector, the demand for innovative solutions that balance design, sustainability, and scalability has never been more critical. This study utilises technology transfers to enhance construction processes, drawing insights from the automotive industry, where advanced technologies and design tools are closely integrated.

In particular, the automotive sector has been used as a source sector of complex frameworks and optimisation methodologies, which, through several stages –from the initial concept to final production- incorporate engineering and design into new product development.

Design for Manufacturing and Assembly (DfMA), the approach that integrates design and engineering to address customer needs while optimising cost, quality, and performance, is key to improving collaboration among departments, aiming to lower costs, accelerate innovation cycles, and boost competitiveness. The industry's lean approach minimises non-value-adding activities, cycle time, and effort, thereby improving efficiency and quality [1]. Additionally, the integration of the supply chain and long-term relationships between OEMs (Original Equipment Manufacturers) and suppliers ensure cost-effectiveness, reduced time-to-market, and improved sustainability.

This research incorporates these strategies to redefine the interaction between design and manufacturing processes in façade construction to enable the creation of lightweight components while reducing material usage and emissions related to production processes; the study integrates WAAM (Wire Arc Additive Manufacturing) because it offers formal freedom and aligns with the principles of mass customisation [2], allowing the production of bespoke components without compromising scalability. Since WAAM requires significant time for layer-by-layer deposition, the research focuses on lattice structures. This approach reduces the area of application and production time while preserving structural efficiency. The choice to analyse WAAM is twofold. On the one hand, the process provides a certain degree of design freedom because it is suitable for manufacturing large components with medium geometric complexity. On the other hand, its recent advancements in both the automotive and construction industries position it as an enabling technology that can facilitate the knowledge transfer that this research ultimately seeks to achieve. Glass fibre-reinforced concrete (GRC) enhances this technology with its versatility and capacity to achieve complex geometries.

INTRODUCTION TO WIRE ARC ADDITIVE MANUFACTURING (WAAM)

WAAM (Wire Arc Additive Manufacturing) is an advanced manufacturing technology that utilises arc welding tools and wire materials to produce metal components [3]. It falls under the category of Directed Energy Deposition (DED), one of the Additive Manufacturing technologies identified by ISO/ASTM 52900:2021 [4]. The WAAM process is widely used in aerospace, automotive, shipbuilding and mechanical sectors because it can produce large and complex parts with high structural integrity and low material wastage [5]. A new multidirectional WAAM process has been developed to enable the creation of complex geometrical features without the need for additional support structures, thus reducing manufacturing time and cost [6].

In the AEC sector, WAAM attracts researchers because it shows promise to produce customised components with reduced lead times. The HPWAAM project [7], led by a UK consortium, has achieved promising advancements in this technology. The project was funded by Innovate UK (the United Kingdom's national innovation agency) [8] and involved Cranfield University and industrial partners such as Foster + Partners and Weir Group [9]. Qualitative data extracted from structured interviews with researchers and professionals in the field highlight that the current research focuses on hybrid methods that combine traditional structural steel production techniques with WAAM to create complex elements that exceed conventional manufacturing capabilities. In this context, traditional manufacturing can be used to post-process WAAM components; for instance, CNC machining can refine specific areas of a beam that require precision geometry or surface finish, such as the ends, holes, grooves, or threaded sections, thereby achieving high levels of accuracy and surface quality[10].

Additionally, conventional methods can be used to construct most of a structure, while WAAM is utilised to enhance it, allowing for optimised structural components. The application of WAAM to pre-manufactured components for addressing complex nodes demonstrates its potential to exploit structural optimisation, enhancing structural performance and efficiency. This approach leads to material savings, weight reductions, decreased environmental impact, increased automation, and lower costs [11].

The research started with identifying specific clusters of approaches in the AEC sector to this technology by examining case studies and reviewing papers (Table 1). One cluster focuses on large-scale component fabrication, using WAAM to produce entire structural elements. An example is the MX3D Bridge in Amsterdam, a 3D-printed steel structure which integrates topological optimisation to reduce material usage while enhancing performance [12]. Another approach emphasises the production of complex interfaces and connectors, where WAAM creates bespoke solutions for joining standardised components. This application is particularly valuable in modular and hybrid construction, as it accommodates complex geometries and irregular angles that traditional methods struggle to address [13]. The prototype for the Wire-Arc Facade (2021), developed by Roland Snooks and the RMIT Architecture | Tectonic Formation Lab, investigated a hybrid approach in which metal was directly deposited onto prefabricated steel plates. This method exploits the strengths of WAAM to create intricate geometric components of the facade, while flat elements are produced from folded sheet metal. Additionally, this approach differs from standard procedures because it uses folded metal sheets instead of disposable base plates as a support of the WAAM components [14].

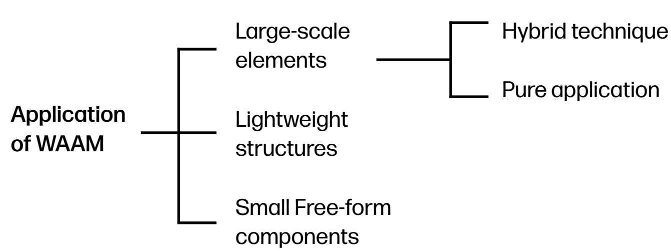

Table 1. Application of WAAM in the AEC sector. Elaboration by the author.

The authors of this research decided to explore aspects of large-scale fabrication, focusing on the application of WAAM where necessary to reduce both cost and production time. Among the different technologies, the "dot-by-dot" printing method has been identified as the most suitable for these types of applications. It requires great attention due to geometrical irregularities [15] but can be used to create lightweight structures, optimising material use and ensuring performance. The manufacturing of lattice structures via WAAM has been facilitated by recent advancements in deposition strategies. Researchers have effectively created pyramidal lattice structures, demonstrating the capability of this method to produce complex geometries [16]. However, the processes of rapid cooling and solidification are relevant factors to consider because they can lead to inconsistencies in the microstructure, resulting in variations in mechanical properties throughout the lattice structure [17]. The microstructural features of WAAM-produced layers can lead to non-uniform mechanical properties, which need to be evaluated in the early stages of the design to guarantee uniform structural performance in load-bearing applications [17,18]. Understanding these effects is important for optimising the performance of WAAM-manufactured components. Ongoing research focuses on refining process parameters and exploring innovative materials to improve WAAM's ability to produce high-performance lattice structures [19]. This demonstrates that the technology requires iterative testing and implementation to reach the intended outcomes.

The data collected so far seems encouraging and may indicate a good potential for the adaptation of these advancements in the construction sector. In addition to the exploration of advanced fabrication techniques, this research also considers materials that complement and enhance the capabilities of WAAM. One such material is GRC, which has some advantages over the other materials in the construction industry.

GLASS FIBRE-REINFORCED CONCRETE (GRC) IN THE AEC SECTOR

Glass fibre-reinforced concrete (GRC) is a construction material that combines glass fibres with a cementitious matrix, offering enhanced strength, durability, and aesthetic versatility. As a subset of fibre-reinforced concrete materials, GRC was a significant innovation in the realm of modern construction [20]. It is increasingly used in construction for structural and non-structural applications, such as facade panels and cladding in general [21]. Thanks to its adaptability and aesthetic appeal, many leading architectural firms use it for applications ranging from simple to complex geometries [22]. Due to its features, the Elizabeth Line project in London (Figure 1) utilised GRC to create a unified and durable cladding system for its central stations, demonstrating the versatility of GRC in large-scale project applications.

Developed by Bryden Wood and GRCUK, the system spanned 32,000 m² and included 27,000 panels, designed to fit the complex geometries of curved tunnels and intersections. The structure was made from laser-cut, folded, and welded stainless steel sheets. Advanced digital tools have been used to ensure accuracy and compatibility with the GRC panels. This project demonstrates how to balance aesthetics and efficiency with the implementation of innovative engineering methods aimed to minimise material use, weight, and the variety of unique moulds. The integration of advanced tools and methodologies such as 5-axis CNC machining and complex management workflows ensured high precision and streamlined fabrication and on-site assembly. The paneling was thoroughly studied to enable faster installation with minimal human intervention, while digital twins and 3D scanning ensured precision within tight tolerances [23].

Achieving this level of efficient design and construction with GRC requires a process of optimisation and standardisation. This involves optimising the base geometry and minimising custom panels to streamline fabrication and reduce costs. The substructure that connects the GRC panels to the building's structural framework can be highly intricate, and that's why one advanced method in GRC applications is the "stud-frame construction", where a prefabricated metal frame, typically made of galvanised steel, is embedded into the panel itself. Within this context, BB Fiberbeton [25], a leading manufacturer specialising in GRC solutions, developed a hybrid system that integrates the steel frame into the cement mix of the GRC. This approach reduces the weight of the substructures, facilitates the installation with minimal mounting points and provides high adaptability for small, medium, and large panels [26]. However, the stud-frame approach, like any other method based on the standardisation of moulds and substructures, has several limitations in addressing the geometric complexity of bespoke designs.

This issue can be overcome with the implementation of Additive Manufacturing techniques, which allow non-uniform material placement and topological optimisation for each panel. The use of standardised steel frames limits the possibility of changing the density of the structural materials precisely where needed, leading to excess weight and decreased flexibility for complex geometries.

To address these challenges, the research explores an automated manufacturing process in which WAAM is used to develop customised sub-structures for GRC panels. While exploring the boundaries of customisation, it is important to consider the application of standards to maintain quality and consistency in manufacturing. The European Standard EN 1169 identifies requirements for prefabricated concrete products, particularly GRC, and outlines key aspects for providing quality, safety, and performance [27]. The Glass Fibre Reinforced Concrete Association (GRCA), the global hub for professionals involved in the design, manufacturing, and application of GRC, is a fundamental source of data [28]. The organisation was founded early 50 years ago in October 1975 to improve GRC quality and comprehension, offering resources and services to architects, engineers, manufacturers, and contractors. The manuals provided by GRCA outline multiple GRC manufacturing techniques that match various application requirements, design specifications, and manufacturing goals.

Among the various techniques, sprayed GRC is the most commonly used and versatile production approach in the construction sector, particularly in complex construction. This technique is preferred because it produces high-performance lightweight GRC components with aesthetic appeal. A further development of this method is the Auto Spray, which improves manual hand-spray techniques by adding automated systems that enhance manufacturing speed and material consistency. The process delivers excellent results when manufacturers need to produce large quantities of flat or moderately complex GRC components such as facade panels. The introduction of automatically sprayed Ultra-High Performance GRC (HPGRC) builds upon this innovation by using advanced materials together with CNC spray technology to achieve exceptional precision and efficiency [29]. The CNC GRC spray station uses a Cartesian-coordinate robotic system with a 5-axis servo drive, allowing accurate spraying on intricate mould geometries. Automated production lines streamline the process by integrating mixing, spraying, curing, and finishing, all controlled through a PLC-based system. These lines are designed for large-scale output, offering enhanced consistency and scalability for modern architectural applications [22].

RESEARCH METHODOLOGY AND FRAMEWORK DEFINITION

Following the principles of the Design Science Research (DSR) methodology, a problem-solving framework that creates innovative artefacts while enhancing theoretical knowledge, this research proceeds through iterative problem identification, artefact creation, evaluation, and refinement cycles [30]. To develop a new perspective on DfMA, the study explores the design and construction of complex architectural geometries, particularly façade components, by balancing cutting-edge technologies with well-established techniques. This balance defines the scope of the research while ensuring that the study remains forward-thinking and practical, aligning the design process more closely with the requirements and constraints of the industry. Aiming for the technological transfer from the automotive to the AEC sector, the SHAPE process, a structured framework designed to execute automotive projects (Figure 2) and developed by Pininfarina, is utilised in this research to enhance the feasibility and efficiency of the design process for the proposed prototype. This approach, found in manufacturing processes, applies a consistent planning procedure [31].

The stages are the following:

- S0: Product Exploration -> Is the idea worthwhile to be explored further in-depth?
- S1: Concept Evaluation -> The ideas have been explored enough to start their detailed development.
- S2: Concept Definition and Evaluation -> Progress against specific delivery targets
- S3: Development -> Progress against specific delivery targets
- S4: Tooling and Process Validation -> Progress against specific delivery targets
- S5: Pre-Series -> Progress against specific delivery targets
- S6: Ramp-Up -> Retrospective on project successes and failures to improve the next project.

In addition, each project will contain checkpoints, such as milestones, design reviews, etc., which will be determined during the concept definition stage.

DfMA strategies aim to optimise the design process to enhance manufacturing efficiency and streamline assembly. The integration of SHAPE in the research allows production-oriented strategic decisions to be made early in the design stage.

In particular, the following DfMA principles are central to this research:

- **Integration with standardisation of Components:**
  Standardisation will affect the interfaces of envelopes, addressing complexity where needed and guaranteeing compatibility with existing façade technologies.
- **Minimisation of Parts:**
  Building upon systematic complexity, the integration of different functional systems reduces the number of components required to support panelling.
- **Ease of Assembly:**
  Assembly guides, as in the automotive sector, support construction teams for an easy to assembly
- **Material Efficiency:**
  The combination of Additive Manufacturing and topological optimisation focuses on material placement only where needed, reducing material waste. As said, standardisation can sometimes increase inefficiency; integrating subsystems enhances material distribution and efficiency.
- **Design for Recycling:**
  Facade components are designed to allow for disassembly and reuse following the principles of Design for Disassembly (DfD). Further integration of circularity can enhance these components toward a more circular life cycle.
- **Collaboration with Manufacturers:**
  The involvement of manufacturers from the early stages of the design ensures that the research brings novelty both on the academic and the

Figure 1: Aesthetic and functional testing of full-scale prototype elements. Image Courtesy of Bryden Wood UK.

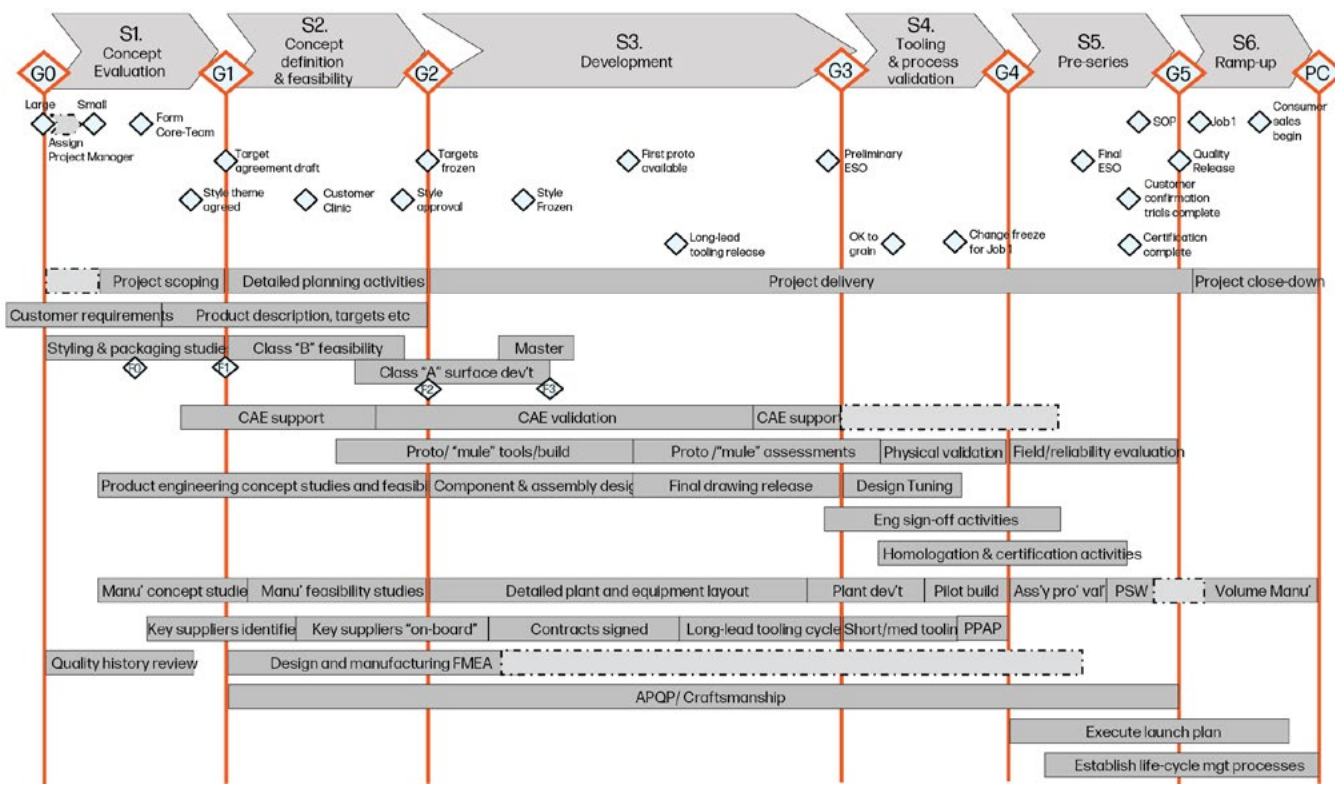

Figure 2: Extract of Shape overview document provided by Pininfarina Spa.

practical side. The study aims to establish a strong network of strategic stakeholders in the development of the process and align design choices with production capabilities.

- **Integration of Mass Customization principles:**
  Additive Manufacturing combined with Automation and Robotic Manufacturing can enable the production of non-standard geometries while maintaining efficiency.
- **Alignment with Sustainability Goals:**
  The integration of substructure and panels minimises material waste and transportation impacts, assessing the embodied carbon of building components. Moreover, as part of a broader DfMA strategy, the components are studied to incorporate Design for Logistics (DfL) principles. In the early design process, logistical constraints- such as component size, weight, and stacking logic- are considered to streamline on-site operations.
- **Reduction of Lead Times:**
  As mentioned, the integration with conventional façade interfaces streamlines the production process, ensuring shorter project timelines.

Recyclability of WAAM metal components, the environmentally responsible production of GRC and other sustainability aspects will be addressed through the "Material Balance" approach. In particular, the investigation into circularity and the use of biobased materials can represent an alternative to cement. However, this direction requires a careful evaluation of structural performance and mechanical properties of the replacement material. The next steps of the research will incorporate these considerations. Moreover, the implementation of these strategies requires manufacturers to participate in design process stages from the beginning. Their expertise can contribute to the development of feasible solutions and, given the industrial orientation of the research, to establish a collaborative network.

Within this context, SHAPE, with its manufacturing-oriented steps, can be used to frame the development of complex components or systems of components. The application of this tool requires appropriate simplification and adaptation. The automotive industry operates at high volumes of production where production lines are optimised to create thousands of identical elements with extremely tight tolerances. In the AEC sector, maintaining the same level of complexity would be impractical since construction projects are generally bespoke. The following six stages simplify the original framework and provide the structure of the research project from conceptualisation to full-scale implementation.

Stage 1: Concept Evaluation

The initial phase focuses on identifying the project's goals. This stage involves brainstorming sessions between industry and academia aimed at assessing the technical and material feasibility of the research. Architectural and functional requirements are defined, although dimensions are not specified to emphasise the manufacturing process and the materials selection. To support this process, initial 3D models and prototypes of lattice structures in other materials such as ABS and PLA are created using conventional 3D printing. In the exploration of lattice geometries, the authors follow the line of investigation built upon prior research conducted at MaBa.SAPERLab, where studies on similar systems and their architectural potential have been ongoing for several years.

Stage 2: Concept Definition & Feasibility

Building on the initial studies, this phase aims to develop a detailed concept and assess its feasibility through a series of technical simulations, which include structural analysis using parametric tools in the Rhinoceros environment. Considering the context of application in facade systems, both thermal and environmental studies determine the performance of the components. Additionally, the integration of WAAM and GRC is defined, focusing on how these technologies interact regarding material behaviours. At this stage, the collaboration with GRC manufacturers will provide insights into the specific mix to be adopted. In parallel, the first tests on lattice structure made with WAAM will be carried out. The outcomes of this phase also include an initial risk analysis that identifies potential challenges and mitigation strategies.

Stage 3: Development

As the project progresses, the research will optimise the designs for manufacturability and scalability. Based on a digital workflow methodology, tests are conducted to validate the performance of the component. An accurate mock-up is created to assess real-world viability and implement the manufacturing workflow and assembly strategies. During this phase, the research addresses sustainability, optimising material usage, and evaluating the feasibility of recycling. The extraction of the metal embedded within the cement-based composite presents significant technical challenges. To address these issues, on the one hand, the research will rely on Design for Disassembly (DfD) principles, taking inspiration from the automotive industry, where the disassembly of components has been integrated into design strategies to enable maintenance, recycling, and efficient material separation. On the other hand, the study will explore the substitution of the traditional cementitious matrix with a bio-based alternative. In doing so, the research aims to advance the field of circularity.

Stage 4: Tooling & Process Validation

After the design optimisation has been achieved, the manufacturing processes and tools need to be validated. This phase involves studies on the application of WAAM deposition and GRC casting workflows within a production line and the integration of robotic systems to support automation and enable a mass customised fabrication process.

Transition toward industrial scalability

Stages 5 and 6 aim at the transition from research to industrial scalability with the goal of testing the feasibility of bringing the prototype into industrial production. Aligned with DfMA strategies, the study is intended to go beyond the experimental phase of digital fabrication and develop a scalable, production-ready system that can be integrated into existing industrial processes and supply chains.

Stage 5: Pre-Series

This stage includes the robotic fabrication of the façade component to complete the validation of the automated workflow and refine both design and production strategies. The final façade mock-up is created and assembled for review, field tests and further refinements. Additionally, this stage produces updated design, manufacturing documentation and installation manuals that offer step-by-step guidance for future implementations.

Stage 6: Ramp-Up

The project's final phase focuses on scaling production to ensure a seamless transition to full-scale deployment. The entire workflow, tools and processes are tested under real production conditions. In line with SHAPE, this stage includes clients' and manufacturers' feedback to evaluate performance and user experience. This feedback loop aims to verify that the final product meets expectations. Ideally, production-ready components are fully realised and implemented by project documentation.

FAÇADE COMPONENT: CONCEPT PRODUCTION PROCESS

Building envelopes require a unique combination of manufacturing, design, construction, and maintenance to perform as expected [32]. Façade design, in particular, represents a complex multi-disciplinary process involving various stakeholders.

This complexity led us to apply a product-oriented framework to streamline the manufacturing process of the prototype, treating it as an independent system within the building structure.

In particular, the production process for the façade component combines advanced technologies such as robotic milling, GRC spraying, and WAAM to deliver a precisely engineered, structurally strong component that corresponds to the design intent. The proposed lattice structure, which is currently in a tentative phase, will be further developed in the upcoming stages of the research to optimise the strength-to-weight ratio and reduce structural loads. The procedure unifies the construction of the entire system within a single, centralised facility (Figure 3).

The following theoretical stages require thorough validation through prototyping, testing, and real-world application to confirm their feasibility and effectiveness. At this stage, specific dimensions are not yet defined, as the initial focus is prioritising the process itself.

Step 1: Milling the Mold

The initial stage implies the creation of a precise mould supporting the following manufacturing processes. Recent research focused on avoiding the use of moulds to reduce costs. In this case, the decision to adopt a mould-based strategy is motivated by the fact that the study is still in the prototyping phase, and the transition to fully industrialised production remains a long-term objective.

Taking inspiration from the automotive sector, where polyurethane moulds are widely adopted, using a robotic arm equipped with a milling tool, the mould is carved according to the panel design (refer to Figure 4). The mould is then treated with a release agent to facilitate the removal of the panel at the end of the next stages.

Step 2: Initial GRC Spray Layer

The first layer of GRC is applied using a robotic arm equipped with a spray nozzle (Figure 5). This uniform layer adheres to the mould and is the base for embedding the metal mesh. Lateral containment depends on the viscosity of the GRC and requires that the mould geometry is specifically crafted to optimise material deposition.

Step 3: Placement of the Metal Mesh

A prefabricated metal mesh (galvanized steel) is placed onto the first layer of sprayed GRC using a robotic arm (Figure 6). The selection of the type of mesh considers factors such as porosity for material penetration, stiffness to resist deformation, and flexibility to accommodate complex

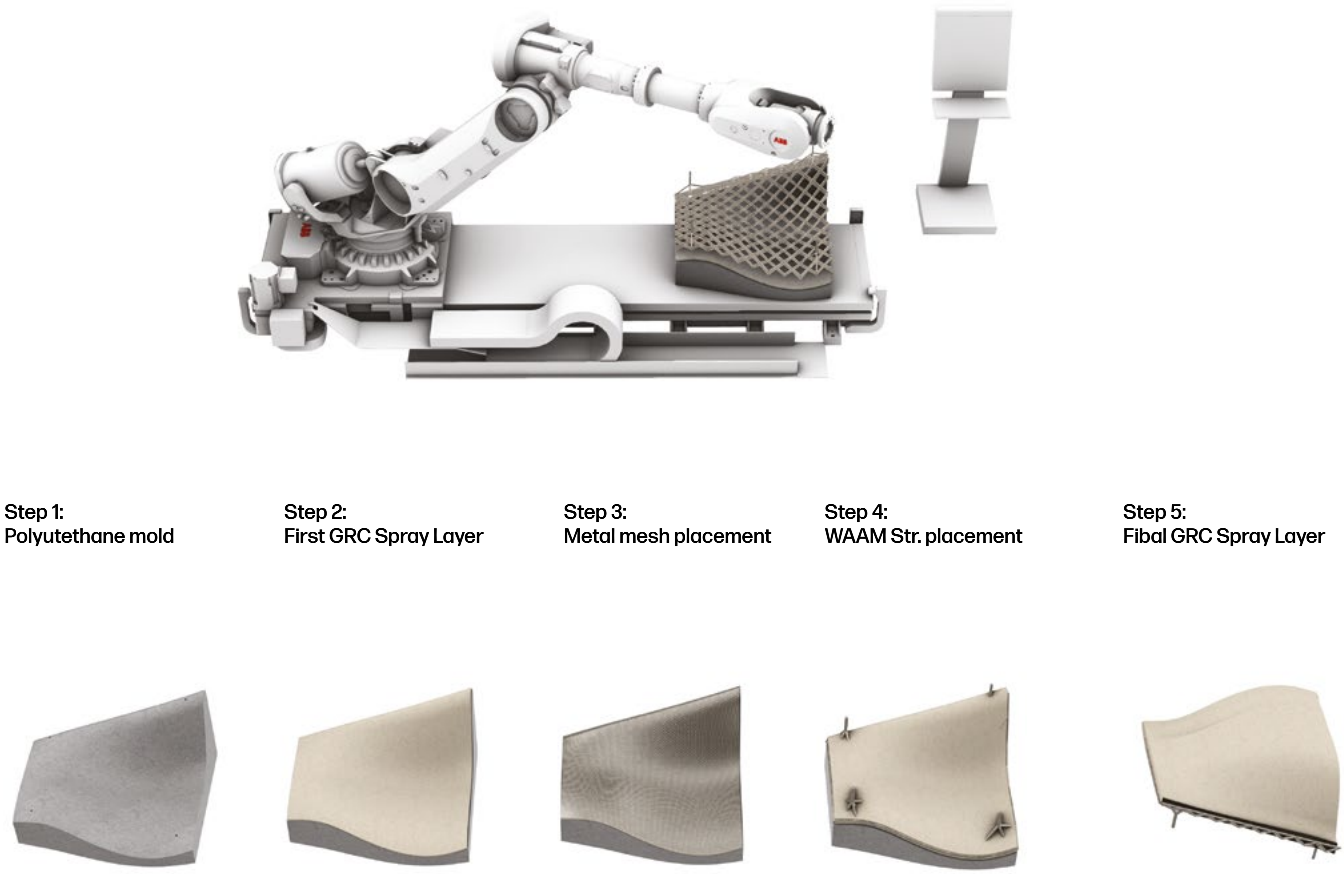

Figure 3: Automated production line. Elaboration by the author.

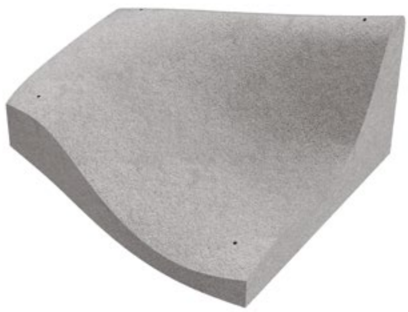

Figure 4: Polyurethane mould. Elaboration by the author.

Figure 5: First GRC Spray Layer. Elaboration by the author.

Figure 6: Metal mesh placement. Elaboration by the author.

Figure 7: WAAM Str. Placement. Elaboration by the author.

Figure 8: Final GRC Layer. Elaboration by the author.

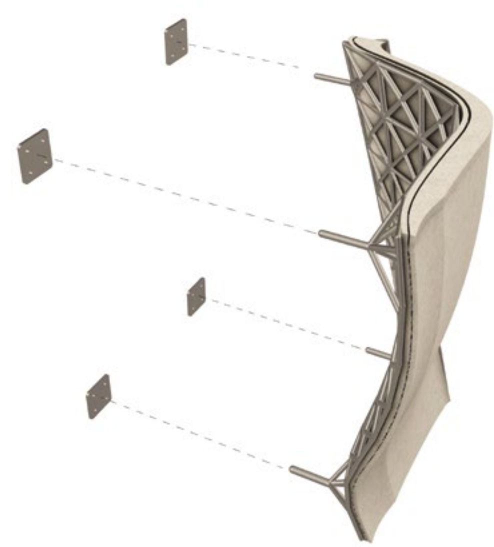

Figure 9: Connection to standard façade interfaces. Elaboration by the author.

geometries. On the one hand, the mesh enhances the tensile strength of the panel; on the other hand, it serves as a stable base for the WAAM lattice structure. The use of a robotic arm within this process aligns with a highly automated workflow where human intervention is minimised, and automation maximised.

Step 4: 3D Printing the Lattice Structure

In this step, a WAAM-enabled robotic arm fabricates the lattice structure onto the metal mesh (Figure 7) using the dot-by-dot technique. The lattice is designed to incorporate connectors for standardised metal plates. From a geometric perspective, the type and configuration of the lattice will be defined using parametric tools, controlling the topology in response to structural loads and performance requirements.

Step 5: Rotating the Components and Applying the Final GRC Layer

A second layer of GRC is sprayed over the lattice to encapsulate the structure, partially embedding it while exposing supports for on-site connection (Figure 8). This stage provides a protective inner finish and prepares the panel for efficient assembly.

Step 6: Connecting to Standard Façade Interfaces

After a specific curing period, depending on the method used, the finished panel, with exposed support points, is transported to the construction site and aligned with the building's façade system (Figure 9). The support points are welded to pre-installed standardised metal plates, following the concept of easy assembly in DfMA strategies.

CONCLUSION AND NEXT DEVELOPMENTS

The research outlined above introduces a methodological shift in how architectural complexity can be approached within a DfMA logic and an industrialised framework. Rather than reducing architecture to repetition and modularity, the study demonstrates how complexity can be structured, scaled, and reproduced by integrating manufacturing processes and cutting-edge technologies. The objective of this study is to go beyond the concept of DfMA based on standardisation to a more advanced understanding of systematic complexity and create a scalable system that balances uniqueness with replicability.

Traditional industrial logic aims to achieve economies of scale by creating identical standardised components that lower production costs per unit with quantity increases [33]. However, this model has created challenges for architectural practice because uniqueness and contextual factors often conflict with mass production. Additive manufacturing introduced a radical change due to its ability to produce geometrically complex, customised components at costs that did not rise with fabrication complexity. The main barrier to scalability exists because the process depends on manual assembly and requires extensive labour to synchronize different stages. The research proposes combining Additive Manufacturing with Robotic Fabrication to develop an automated workflow that unites component production and assembly functionality. This methodology creates conditions for mass customisation transitions through process and form intelligence integration.

The proposed production process draws qualitative data from literature reviews, case studies, and expert insights. However, this conceptual foundation requires quantitative data to optimise the process and ensure its real-world applications. A thorough knowledge of the material properties, together with mechanical properties and procedural characteristics of the hybrid system, is essential for this project.

The project will gather data during the prototyping phase by analysing digital simulations and physical tests focused on WAAM and GRC interactions. The analysis of mechanical behaviour between these materials at their interface is a crucial requirement. The cement-based matrix of GRC contains fine aggregates as its primary composition, yet its interaction with WAAM metal lattice structures needs to be investigated concerning the matrix-substructure connection. WAAM generates surfaces through its dot-by-dot and layer-by-layer deposition, which creates irregularities that produce micro-ridges along with textural roughness. This characteristic suggests potential benefits instead of becoming a weakness. Moreover, WAAM surface irregularities share similar features with traditional steel bars in concrete, which could enhance mechanical bonding with the matrix material. The analysis of WAAM lattice and sprayed GRC composite behaviour is needed to investigate their bond strength and shear transfer properties. The validation of this hypothesis requires exact measurements of the adhesion strength and crack propagation patterns at the point where the GRC matrix meets fibres and WAAM structures. Geometric and dimensional parameters will require an iterative process of adjustments. The performance of the system depends on three main factors: the GRC layer thickness, WAAM lattice geometry and spacing, and the entire component's dimensions.

At this point, the potential partnership between Pininfarina and a GRC manufacturer can ensure that the production process follows industrial requirements. In parallel, the research benefits from the Material Balance approach, which has long been involved in experimental research that merges physical prototyping with digital modelling, incorporating material behaviour as an active parameter in the design process. The WAAM prototyping phase will encompass mechanical metrics—including tensile, compressive, and flexural behaviours—and production variables like deposition speed, material consumption, thermal distortions, and energy use. Furthermore, we will evaluate environmental performance metrics, such as the thermal and acoustic insulation values of the composite panel, especially regarding its application as a building envelope system. In addition, issues related to circularity will be addressed, including the potential for disassembly, reuse, and recycling of materials at the end of the component's lifecycle. In conclusion, the approach will consist of working simultaneously on the material and computational sides of architecture, enabling a deeper integration between form, performance, and fabrication.

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LIGHT-WEIGHT HOLLOW ADDITIVE MANUFACTURING

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Phillip Wüst
Nastasia Sysoyeva
Oliver Tessmann

This article examines additive manufacturing and robotic fabrication methods for hollow, lightweight structures in the field of architecture, engineering, and construction (AEC) industries. This article examines hollow, lightweight mineral building elements and their manufacturing methods. More specifically, this article explains the novel additive manufacturing method Blow Extrusion (BX) in detail. Blow Extrusion is an extrusion-based method for large-scale 3D printing of hollow strand structures. Blow Extrusion (BX) enables the production of lightweight, air-filled, strand-based structures significantly reducing material use while maintaining structural integrity.

Hollow structural elements have historically played a critical role in reducing material consumption, optimizing weight, and improving construction material efficiency in construction. For instance, RotoForm, a sequential robotic casting process for mineral-based materials, is a robotic additive manufacturing method, resulting in hollow building elements. Beside the technical insights, this paper outlines the potentials of additive manufacturing in enhancing reduction material consumption through design and manufacturing procedures for cavities. The paper discusses the mechanical challenges, computational frameworks, prototyping challenges, and future applications of these methods in structural design, prefabrication, and lightweight construction.

INTRODUCTION

Hollow building elements have been long in use in architecture, engineering, and construction (AEC), serving as an essential and straight forward strategy for reducing material consumption, enabling lightweight structures, and optimizing the overall weight of construction. From ancient Roman concrete vaults with embedded voids to modernist explorations in lightweight prefabrication, the principles of hollow construction have continuously evolved alongside architectural and technological advancements.

With the emergence of digital fabrication, robotics and automation, the principles of light weight hollow structures are to be redefined through novel fabrication techniques. The integration of additive manufacturing and robotic construction allows for unprecedented control over material placement, enabling the realization of geometric complex, light-weight hollow structures. These advancements not only enhance material consumption efficiency but also open new design capacities for precise material placement and deposition.

This article examines three emerging material systems and fabrication techniques that harness robotics and additive manufacturing for the creation of lightweight, hollow building components. The first, RotoForm, sequential robotic casting, explores rotational additive manufacturing for shaping hollow building elements within mineral-based materials (Tessmann & Mehdizadeh, 2019). This additive manufacturing method investigates the capacities of activating kinetic behavior through robotic sequential casting and weight distribution inside the cavity. (Mehdizadeh & Tessmann, 2024). The second, Blow Extrusion (BX) in Large Scale reimagines extrusion-based fabrication to form large-scale, air-filled hollow strand 3D printing (Mehdizadeh et. al. 2024) . Through these case studies, this article highlights the capacities of light weight hollow additive technique BX more in detail on mechanical, digital framework developments.

BACKGROUND; PRECAST HOLLOW LIGHTWEIGHT STRUCTURES

The Barrel vault made of terracotta tubes employs the Hollow clay elements have been employed since the Roman Empire for building vaults and ceilings. These elements serve to either minimize the overall weight of the structure or to create large-span vaulted spaces by assembling conically shaped hollow tubes in an interlocking manner (Lancaster, 2015) (Fig.1. a.). By the late 19th century, hollow clay elements gained widespread use in ceiling construction (Fig. 1. b.). The ability to mass-produce these tubes as standardized products was the key factor in their widespread adoption. These tubes were manufactured using drainage pipe presses from the 1870s onward. Their popularity led to the development and patenting of numerous variations in France, England, Germany, and the U.S. up until the 1930s. These innovations focused on improving durability but also on reducing weight through hollow sections. The modular logic of these elements is designed to position the hollow clay tubes and then add reinforcement between them. Afterward, cast concrete is placed on top of them to increase the width of the span between two structural beams (Fischer, 2009) (fig.1. b.). These structural span elements increase the overall load-bearing behavior of span, and at the same time, they serve as lost formwork to cast concrete on top of them.

The hollow-core slab

The hollow-core slab is a widespread precast hollow concrete floor construction system (Fig. 2.a.b.). Due to its cavity, this system provides high material efficiency with significantly less weight. A large machine extrudes the concrete slabs horizontally on the bed (Elliott, 2017). The manufacturing of these elements is very fast and efficient due to the extrusion process. However, the repetitive logic and standardization restrict them to planar shapes, limiting their adaptability.

Both bridge and slab systems provide higher structural performance in relation to material mass. Structural height is achieved through the hollow section without excessive material consumption. The use of cavities formed by plastic balls inside concrete slabs is a common practice, particularly in the 'Cobiax Technologies' (Fig. 2c) system, patented in 2004 (Haag et al., 2005).

'Bones', precast system of Miguel Fisac

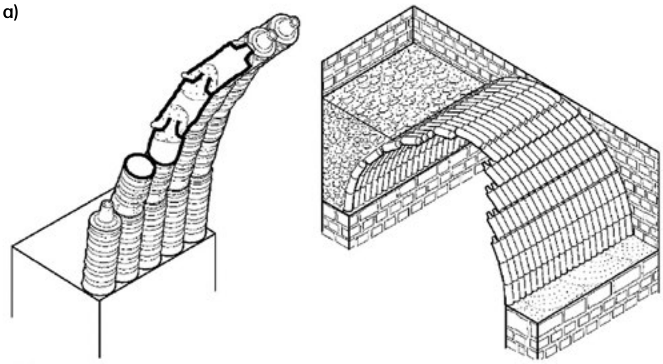
A great example of expanding the design capacities of hollow structural elements is in the work of Miguel Fisac, the modernist architect (*Carbonero*, 2003.) developed a structural system based on lightweight, hollow concrete elements. His patented system, known as 'Bones,' allows for the construction of long-span roofs by utilizing prestressed components that function in both prestressed and post-tensioned states (Fig. 3.a.). Fisac expanded this approach into a broader range of building elements using the same prestressed material principles (Fig. 3.b.) (*Mostafavi*, 2003.). Within the system 'Bones' Fisac had brought the Idea of bringing the water drainage and even light distribution in the spaces under the bone beams and still be light weigh. Geometry satisfies the function integration in this case. Fisac had built Lang post-tension span buildings with his system in 60's such as center of hydrographic studies in Madrid 1960-1963.

A hollow lightweight mineral material system; RotoForm

The emphasis on the role of material behavior and its embodiment into a design procedure describes much of the material system's theoretical framework. This emphasis also includes the machinery and computational design framework for specific materialization within the design-build system. Considering this theoretical framework, this article focuses on material systems in the field of additive manufacturing, which result in hollow objects.

RotoForm is a research trajectory at TU Darmstadt, targeting digital additive manufacturing of hollow lightweight building elements. The material system RotoForm exists through the behavior of mineral materials, sequential casting, and the phase-changing characteristics of mineral building materials from liquid to solid. This additive materialization technique allows the addition of continuous layers of material inside the formwork. Each layer results in a thicker outer shell and a smaller cavity inside the hollow object (Fig. 4).

The digital fabrication technique RotoForm operates through a specific machinery setup, a digital design-simulation framework, and the design of mineral material flew behavior and rheology (Mehdizadeh et al., 2022). The rotational casting machine continuously spins the formwork at a steady speed and in a designated direction. This movement ensures an even distribution of material across the a)



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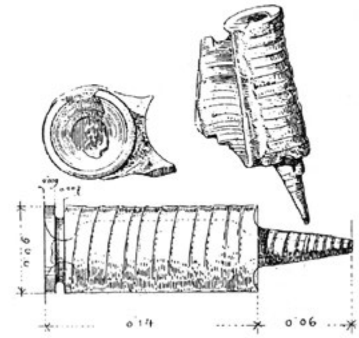

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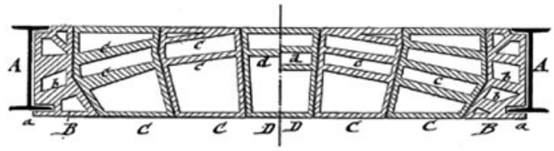

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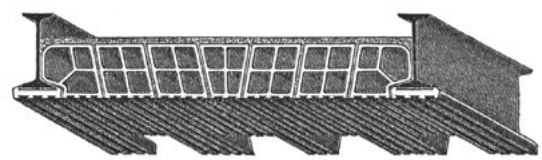

Figure 1: (a) barrel vault made of terracotta tubes. hollow stone conical/tubular vessels, with interlocking connections with no iron support system (b) a single hollow clay pipe vault element 500 B.C. Drawing from (Durm (1905), S.299; Storz (1994), S.10.) (c, d) a patented hollow stone ceiling by Austrian engineer Friedrich von Emperger, founder of the journal "Beton-und Stahlbetonbau," in the U.S. in the 1890s. The positioning of the material in this section is very similar to the compression force diagram in the structural elements. (Drawing: Sitzungsberichte der Bezirksvereine. In: ZdVDI 40 (1897), S.1008.)

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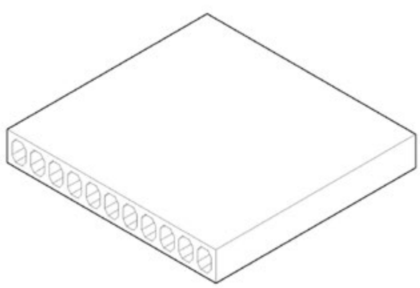

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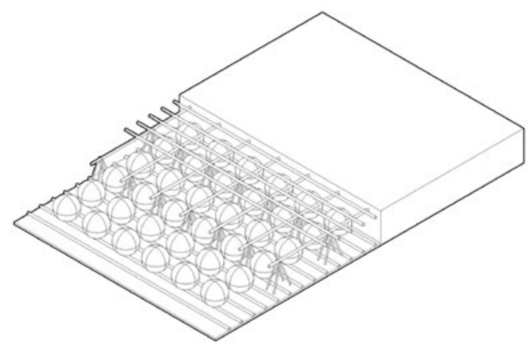

Figure 2: (a) Deep hollow-core floor unit section (b) Cobiax technologies hollow core system.

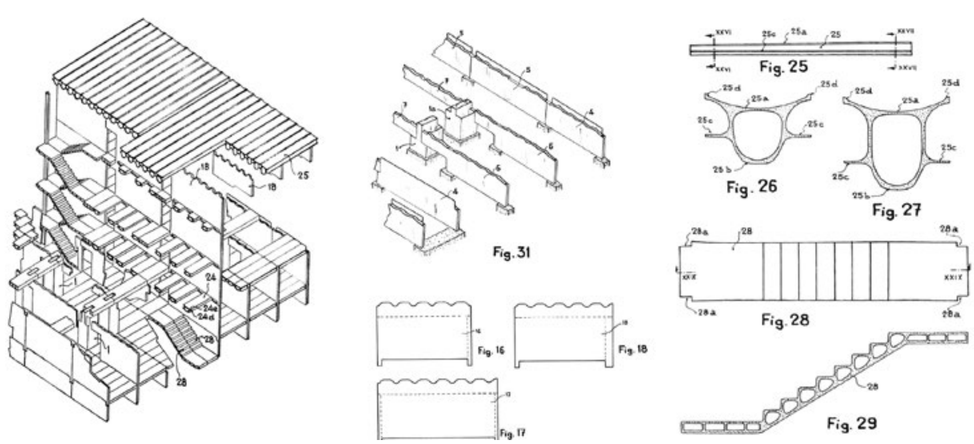

Figure 3: (a) The ceiling element, “Bones,” of Miguel Fisac and himself. (b) Housing prefabrication system 1965 drawings of Miguel Fisac (Photo credit: the Miguel Fisac Foundation, Image reprinted from AV Magazine monograph on Miguel Fisac, 2003, edited by Galiano Frampton, Mortazavi.)

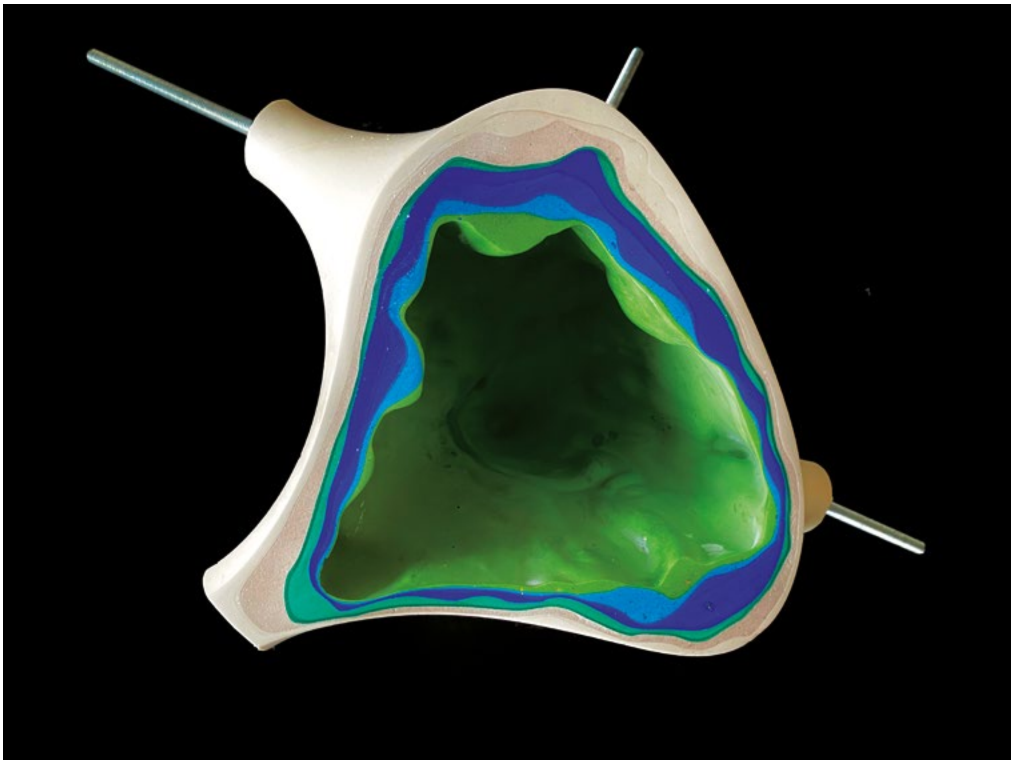

Figure 4: RotoForm node, rotationally cast within a closed, hyperplastic, pre-tensioned membrane in eight layers, using uneven rotation parameters and trajectories. The node materialized with a water-based polymer dispersion and mineral material. DDU (Photo: Samim Mehdizadeh, 2018)

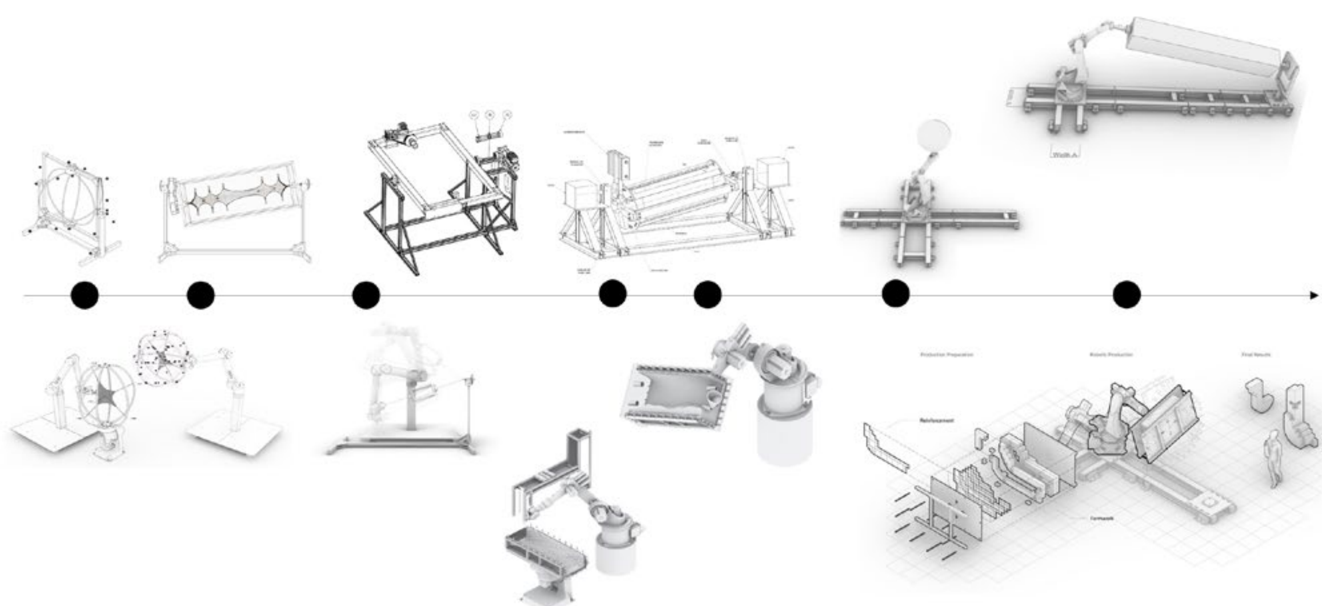

Figure 5: RotoForm machinery setups were developed, built, and tested at DDU, PMD of TU Darmstadt, and Spannverbund GmbH. Between 2018 and 2022, these setups were used to examine a diverse range of spin trajectories and machinery configurations concerning implementation, setup, and the fabrication of hollow, lightweight elements. (Drawings: Samim Mehdizadeh, Spannverbund GmbH. PMD TU Da. Joschua Schäfer)

entire formwork, preserving consistency in both sequence and duration. The three-dimensional motion results from two rotational axes, typically perpendicular to one another, operating at varying speed ratios.

Machinery setup, Robotic sequential Casting

Expanding the machinery setup is a crucial part of this research trajectory to explore the role of machinery configurations, rotational casting parameters, and the expanded capacities of this additive manufacturing method for hollow, lightweight elements. Robotic setups and specific rotational trajectories have been investigated using both small- and large-scale robotic systems, which have the potential for transition to large-scale machinery setups (Fig. 5).

HOLLOW LIGHTWEIGHT AND ADDITIVE MANUFACTURING; BLOW EXTRUSION (BX)

Blow Extrusion (BX) 3D printing is an innovative additive manufacturing (AM) method that enables the production of hollow strand structures (Tessmann et. al. 2022) (Fig. 6.). Our offered BX approach integrates Fused Granular Fabrication (FGF) and Fused Filament Fabrication (FFF), combining multi-material 3D printing, blow extrusion, robotic fabrication, and computational design. By utilizing hollow strands with adjustable cross-sectional diameters, our technique significantly reduces material and resource consumption.

The use of large-scale 3D printing with thermoplastics is rapidly expanding in technology-driven research within the architecture, engineering, and construction (AEC) industry. Real-world construction applications, such as interior walls (*Aectual | 3D Printed Architecture & Interiors, actueccessed 2024*), acoustic elements (Setaki et al., 2023), exterior façade elements (Sarakinioti et al., 2018), and concrete formwork (Jipa & Dillenburger, 2021), have been used in research and practice. BX 3D Printing decreases material consumption while creating lightweight and robust elements.

The additive manufacturing method BX significantly decreases material usage—by up to 85%—compared to printing with solid cross-sections, while also offering precise regulation of material flow. Additionally, this approach facilitates large-scale 3D printing of hollow strands with adaptable cross-sections by adjusting airflow during extrusion to control strand inflation (Fig. 7).

Here we outline the design-to-fabrication framework and the mechanical development of Fused Granular Fabrication Blow Extrusion (FGFBX) and multi-material Fused Filament Fabrication Blow Extrusion (FFFBX) with variable sections. Additionally, the studies and prototypes showcasing some of our early-stage research outcomes for construction industry applications, such as lightweight façade elements, formwork systems, and displacement bodies in concrete ceilings.

Technical Background

Large-scale additive manufacturing with thermoplastics presents several challenges. In the AEC industry, optimizing plastic usage and reducing printing time are critical concerns. From a mechanical standpoint, key issues include limited material throughput, thermal deformations, and the time required for solidification. This research addresses these challenges by improving both AEC applications and mechanical properties through the transition from conventional solid filament deposition to the extrusion of hollow strands.

The process utilizes ring-shaped hollow strand extrusion with a coaxial nozzle, allowing for controlled pressure adjustments within the extruded strands, resulting in variable cross-sections. This approach enables the production of hollow strands rather than solid plastic layers, significantly lowering material consumption per unit volume. Additionally, the encapsulated air enhances cooling efficiency, leading to increased throughput and faster printing speeds.

The introduction of 3D printing for hollow strands using filament feedstock was first proposed by Hopkins (Hopkins et al. 2020). More recently, (Leschok et al., 2024) from DBT at ETH Zürich explored an alternative approach utilizing pellets as feedstock for robotic 3D printing of hollow strands. Their method, based on Fused Granular Fabrication (FGF), achieves a material throughput of 50 kg/h, whereas Fused Filament Fabrication (FFF) is significantly lower, reaching only 0.5 kg/h. The stark 100-fold throughput difference highlights the practical limitations of filament-based methods for large-scale hollow strand fabrication.

Blow Extrusion Machinery; Thechnichal Development

The core development of this research involves a series of prototypes and process evaluations through continuous monitoring. Throughout our studies, we have explored and demonstrated the integration of this advanced extrusion method in two key directions: (a) FGFBX, which enables mono-material extrusion from pellets with variable cross-sections, and (b) FFFBX, which supports multi-material extrusion from filaments, also with adjustable cross-sections.

At this stage, prototyping has played a crucial role in assessing feasibility and determining the potential applications of both FGFBX and FFFBX. A significant aspect of the technical development has been addressing mechanical challenges to refine and optimize the extrusion process.

Mechanical Challenges

The mechanical design of the print heads presents several key challenges, including: (a) material throughput, (b) nozzle design, and (c) precise air control for inflation.

Digital to Physical Framework for Robotic 3D Printing

The digital workflow for these processes integrates a geometric slicer, robotic simulation, and real-time communication between the UR10 robotic arm and a custom-built extruder setup. This streamlined digital-to-physical transition begins with 3D modeling and parametric design in Rhinoceros and Grasshopper. Our custom slicer enables the programming and visualization of variable cross-sections, ensuring precise material deposition. Additionally, a dedicated client software facilitates real-time data transmission between the robotic arm and extruder system. For efficient synchronization, we utilize an open API framework (Moonraker/Klipper), enabling coordinated control over extruders, air pressure, and robotic movements (Fig. 8).

Prototyping and Results

By replacing polymer with air, we achieved a material reduction of approximately 65% without expanding the strand further, and up to 85% by increasing its diameter by a factor of 1.5 using our BX technology (Fig. 7). During the initial prototyping phase, we first explored the maximum printable dimensions and assessed the UR10 robotic arm's operational reach (Fig. 10). Next, we experimented with variations in the hollow strand's cross-section (Fig. 9). The demonstrator models were fabricated using transparent PETG for the FGFBX process, while the FFFBX method utilized four-color PETG (CMYK—cyan, magenta, yellow, and black).

Hollow lightweight Robotic Blow Extrusion

Using the robotic setup and FGF allowed us to explore the capacities of continuous large-scale prototyping with BX. The digital design-to-fabrication setup allows us to use both FGFBX and FFFBX extruder setups with any robotic arm machine, using the same digital framework. We have challenged the system's scaling in two setups for vertical and horizontal printing (Fig. 10).

The vertical printing setup with the UR10 robotic arm has been used to print 1100 mm long segments within the diameter of 40–60 cm in a variable shape. Our robotic setup, extruder, controlling system, and digital framework allowed us to vary the diameter of hollow strands systematically from 10 to 20 mm in this prototype. The Hight of the vertical prototypes are limited to the robotic arm and not the process. Within a larger robotic setup, the printing area limits can be eliminated.

These prototype segments demonstrate the significantly increased printing velocity in comparison to 3D printing with solid strands. Each segment has been built with approximately 5000 g of PETG granules, which showcases the lighweight elements through hollow additive manufacturing (Fig. 11. & 12).

Throughout a series of experiments using robotic setup and Blow extrusion for horizontal printing we explored the manipulation and tweaking the blow extrusion parameters. The results demonstrate great potential for varying and manipulating the Diameter of hollow strands immediately up to approximately 4 Times. (Fig. 13 &14).

TECHNICAL DISCUSSION

Using the robotic setup and FGF allowed us to explore the capacities of continuous large-scale prototyping with BX. The digital design-to-fabrication setup allows us to use both FGFBX and FFFBX extruder setups with any robotic arm machine, using the same digital framework. We have challenged the system's scaling in two setups for vertical and horizontal printing. The vertical printing setup with the UR10 robotic arm has been used to print 100 cm long segments within the diameter of 40–60 cm in a variable shape. Our robotic setup, extruder, controlling system, and digital framework allowed us to vary the diameter of hollow strands systematically from 10 to 20 mm in this prototype. These prototype segments demonstrate the significantly increased printing velocity in comparison to 3D printing with solid strands. Each segment has been built with approximately 5000 g of PETG granules, which showcases the extremely lightweight elements through hollow additive manufacturing.

CONCLUSION AND OUTLOOK

This paper emphasizes the crucial role of additive manufacturing in the materialization of hollow structures. Within the scope of this article, two additive manufacturing procedures are introduced, each utilizing specific machinery setups. Hollow structures in the construction industry hold enormous potential for significantly reducing material consumption.

Minimizing material use is a highly effective and straightforward strategy that contributes to sustainability goals in general and the AEC industry specifically. Material reduction is essential for building materials such as concrete and plastics, which constitute a large portion of materials used in construction and have a significant negative environmental impact.

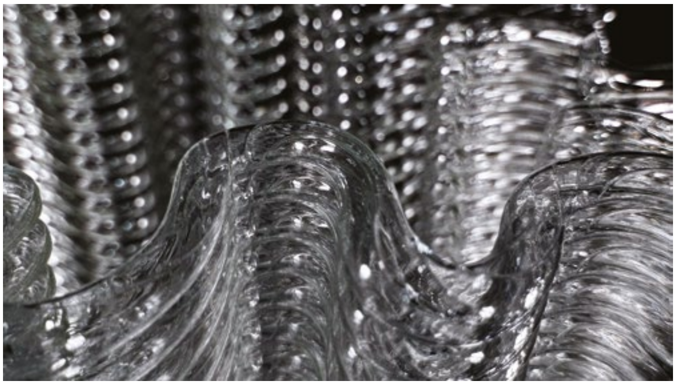

Figure 6: Hollow-strand 3D printed Prototype in vertical printing setup with FGF blow extrusion method .

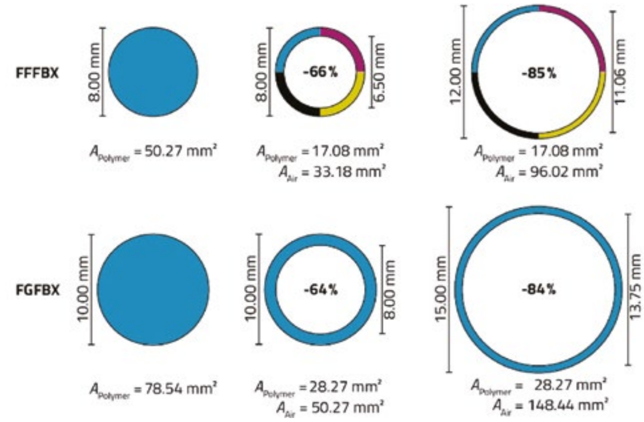

Figure 7: Material reduction in percentage compared to the full cross-section (left) for hollow strands produced using FFFBX and FGFBX without inflation (center) and with an increase in size by a factor of 1.5 (right) by Blow Extrusion (BX) where A represents the area.

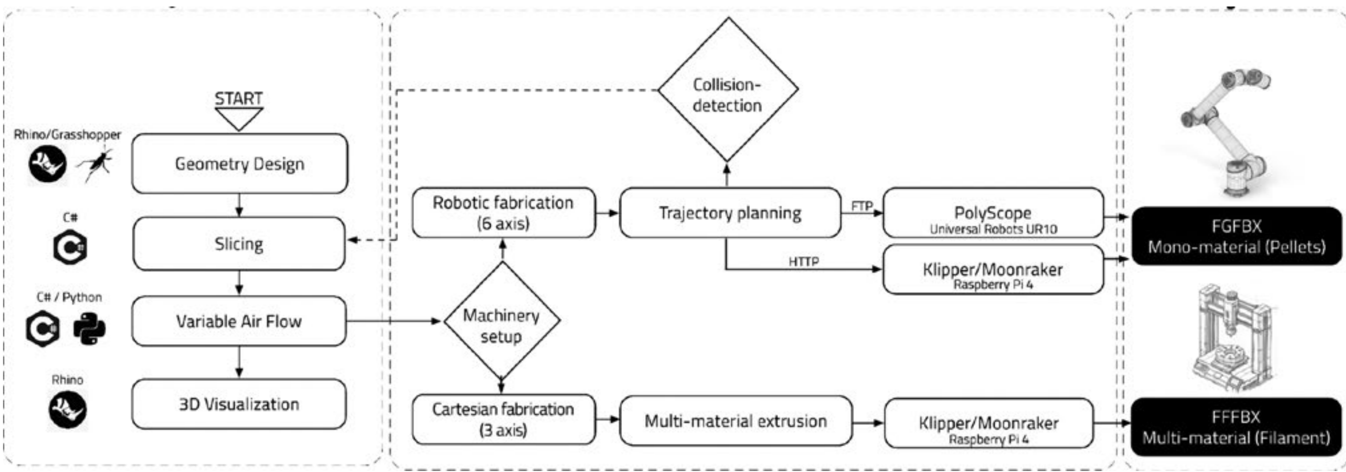

Figure 8: the Digital design to materialization framework. Made of costume made slicer and Data streamline between the machinery and several synchronize actuators.

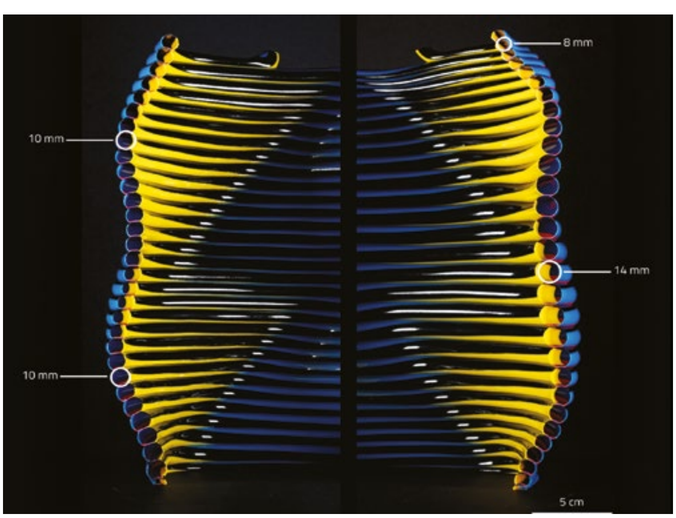

Figure. 9: FFFBX with four filaments in different colors. The two prototype sections compare the effects of constant and varied parameters for BX. On the right, the printing parameters are adjusted continuously, increasing the section size by up to 1.66 times. The hollow strand is printed with multi-material FFFBX. (Material: *Extruder* PETG (C, M, Y, K); Measurements: *Keyence* VR-5200, n=5, λ c = 25 mm)

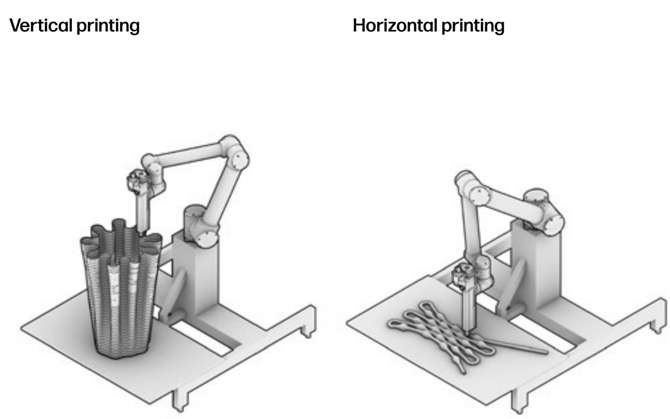

Figure 10: (a) vertical and horizontal printing setup plan.

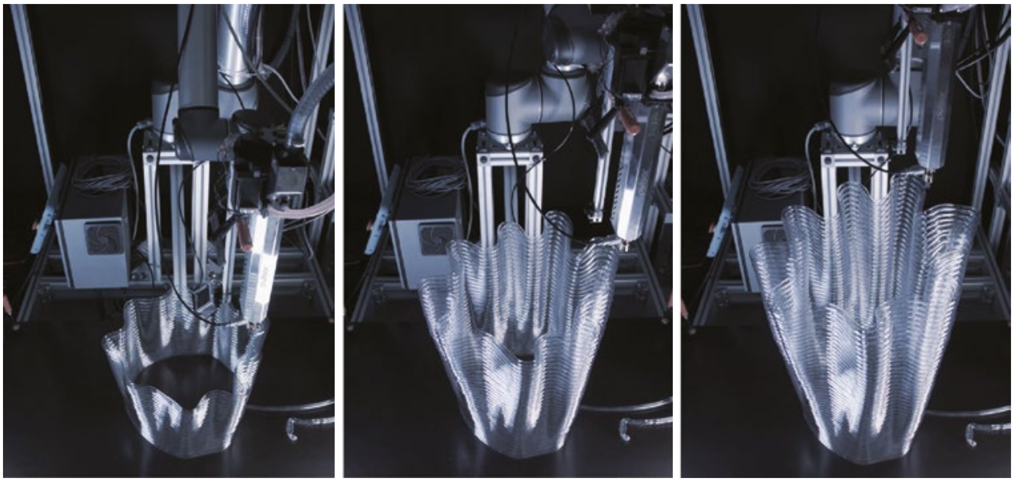

Figure 11: The actual robotic 3D printing is set up for large scale vertical 3D printing using the UR10 robotic arm and FGFBX extruder. From left to right the print progression. Time between images: approx. 60 minutes.

Figure 12: large scale Prototype Blow extrusion in two segments at maximum printing area of the robotic setup with UR10 robotic arm. Each segment of prototype is 1100 mm high and took about 300 minutes to print. Each segment only uses 5 Kg of PETG for print. (Photo Credit: Samim Mehdizadeh).

Figure 13: the results of blow extrusion in FGFBX procedure and PETG material varying the pipe diameter through variable material flew, air pressure. The hollow strands Diameter varies from 10mm to 45mm (Photo credit: Samim Mehdizadeh).

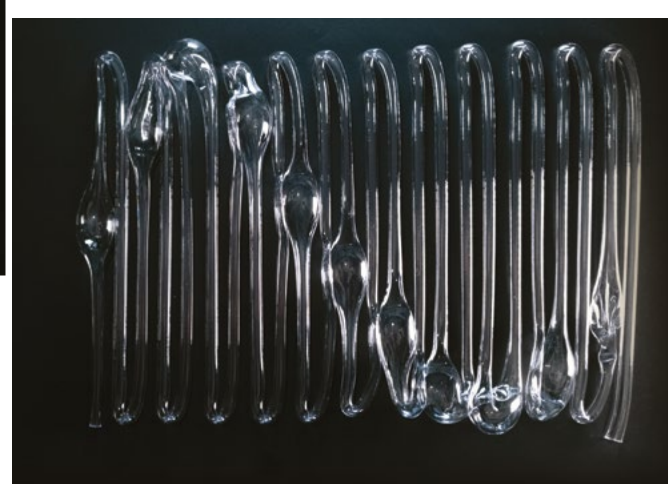

Figure 14: The results of blow extrusion in FGFBX procedure and PETG material varying the pipe diameter through variable material flew, air pressure. The hollow strands Diameter varies from 10mm to 45mm (Photo credit: Samim Mehdizadeh).

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