ADDITIVE MANUFACTURING in CONSTRUCTION

Investigation of the construction industry's biggest challenges in terms of resource consumption and sustainability, and potential solutions that include additive manufacturing.

Danish AM Hub

ACKNOWLEDGEMENTS

Danish AM Hub developed the analysis in collaboration with several partners and stakeholders (academia, business and industry, educational institutions, start-up environment).

- As active partner, ConTech Lab - a part of Molio has supported Danish AM Hub in investigating the challenges and needs of the construction industry, providing contacts and facilitating the workshops. From the collaboration with Danish AM Hub, ConTech Lab - a part of Molio acquired experiences in using Additive Manufacturing (AM) technology in construction and in the development of innovative solutions to address some of the challenges in the industry.

- HD Lab, digital specialists in the construction industry, focused on creating better results and efficient collaboration on construction projects using effective ICT management and digital solutions, supported Danish AM Hub in leading the workshops with the stakeholders from the construction industry, and providing valuable insights in the development of the report.

- Research institution and university laboratories has been contacted, such as the Royal Danish Academy, Institute for Advanced Architecture of Catalonia (IAAC), Swiss Federal Institute of Technology (ETH Zurich), Technical University of Denmark (DTU), and University of Southern Denmark (SDU), to create, share and collect experience and research on AM.

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EXECUTIVE SUMMARY

The construction sector is a major contributor of greenhouse gases globally and has a critical role to play in meeting climate change targets. However, lower productivity and a lack of technology adoption compared to other industries are slowing its decarbonisation path.

Danish AM Hub has conducted an analysis of the construction industry's biggest challenges, identifying key focus areas based on reduction of emissions, waste and resource consumption, the integration of sustainable materials and the level of flexibility of the system.

This report explores the transformative potential of Additive Manufacturing (AM) in meeting these challenges, particularly through the integration of bio-based materials and the development of modular, adaptable systems.

Key Findings:

- The adoption of AM in construction is currently hindered by regulatory barriers and a lack of standardized testing protocols.
- AM enables precise material usage, minimizing waste and resource consumption while enhancing design flexibility and circularity.
- Low Emissions Materials with High Flexibility is the most promising domain for leveraging AM to meet sustainability goals.
- Integrating bio-based and recycled materials with AM technology offers dual benefits: reducing emissions while fostering design innovation.
- Design for disassembly and reuse is crucial to extending material lifespan and advancing circular economy principles.

Recommendations:

1. Focus on bio-based and recycled materials – Develop AM-compatible components that incorporate biogenic and circular materials to enable sustainable, adaptable construction.
2. Lifecycle integration – Apply Life Cycle Assessments (LCA) to ensure environmental sustainability throughout a component's lifecycle.
3. Regulatory and standardization efforts – Advocate for industry-wide guidelines and certification standards to support the adoption of AM-based construction methods.
4. Collaborative development and knowledge sharing – Build strategic partnerships between bio-based material producers, AM technology providers, and research institutions to overcome adoption barriers.

DANISH AM HUB

Danish AM Hub, initiated by the Danish Industry Foundation, is the focal point for additive manufacturing in Denmark. The ambition of Danish AM is to strengthen the competitiveness of Danish manufacturing companies by promoting the use of AM, and to help them take the first steps towards a future with less waste, material, transport, and CO2 emissions.

To explore how AM can contribute to solving some of the biggest challenges related to sustainability, use of resources, production of waste, and lack of adaptability and flexibility in the construction industry, Danish AM Hub has funded and developed the AM Village project, a space for knowledge creation, innovation, and dissemination.
The AM Village can serve as a means to analyse the challenges of making cities more sustainable and to identify the gaps between the current state of the industry and the future possibilities of using AM technology.

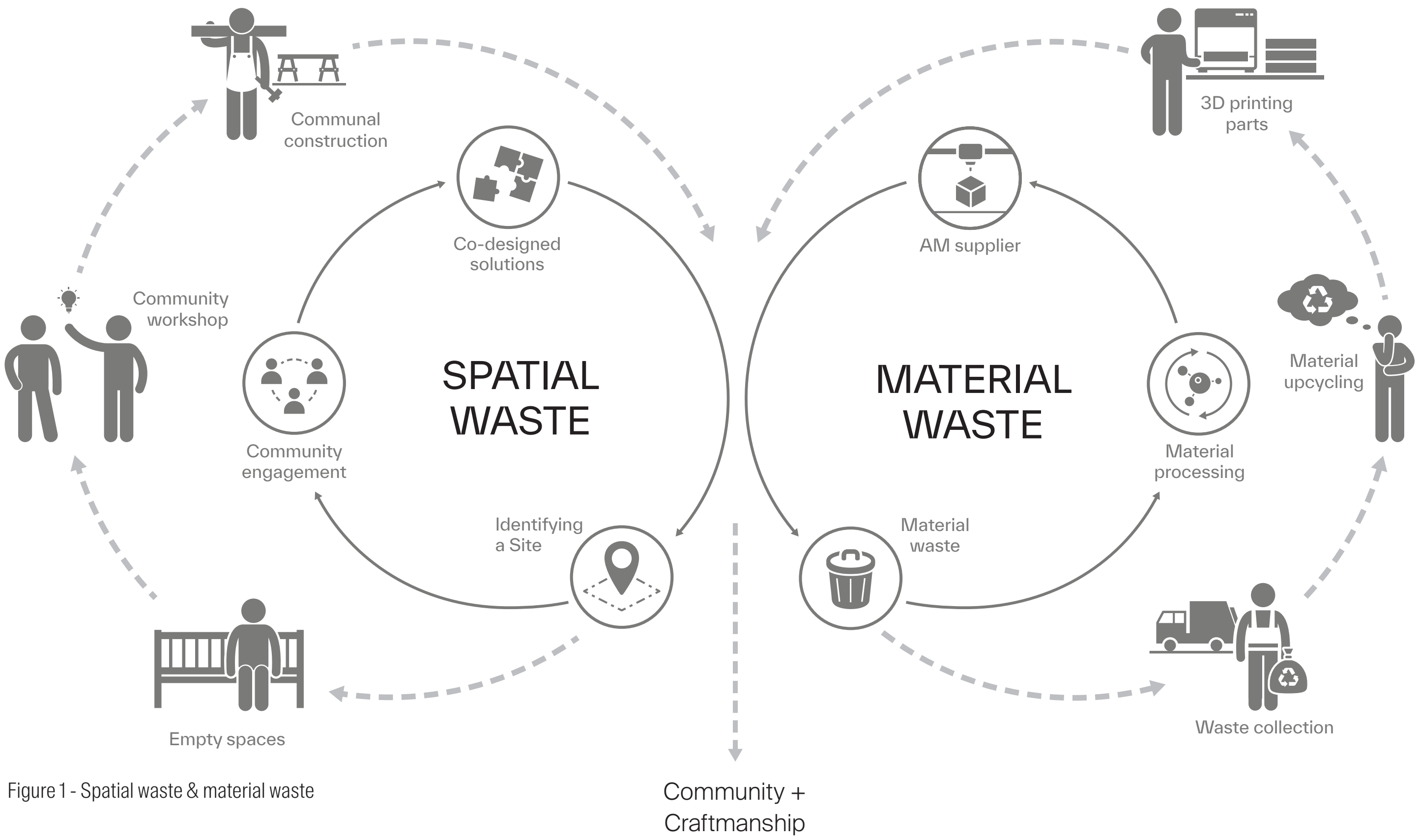


Figure 1 - Spatial waste & material waste

The AM Village concept

The goal of the AM Village is to transform construction from a scaled, uniform, and polluting process to a flexible system focused on sustainability and circularity, using AM technology to realise the potential of intelligent design and adaptive reuse.

A core value of the AM Village is the use of space and material waste within the local urban environment. Additive manufacturing allows a fast and flexible construction process and the possibility to reuse low quality construction waste.

INTRODUCTION

The built environment has a significant impact on the quality of life, the economy and society. In Denmark, it is responsible for 35 per cent of the materials used, 37 per cent of the total waste produced, and 30 per cent of CO_2 emissions.

For decades, the construction sector has suffered from significantly lower productivity and lack of technology adoption compared to other sectors, with construction projects often subject to cost and time overruns. More efficiency, innovation and high levels of technical and environmental performance are therefore needed to meet the climate change targets.

An effective approach can be found in the increased availability of digital technologies and innovative materials that have the potential to significantly improve the quality of the built environment.

Additive Manufacturing (AM) has already transformed the manufacturing industry and offers an extraordinary opportunity to explore innovative approaches to sustainable constructions, allowing increased flexibility, optimized supply chain and minimized waste, leading to a potential reduction in Greenhouse Gas emissions (GHG).

Danish AM Hub has received a grant from Realdania to conduct an analysis of the construction industry's biggest challenges in terms of resource consumption and sustainability, and to try to formulate one or more potential solutions that includes AM.

The first phase of the analysis, developed in this report, aims to examine the current status of AM applications, the challenges and opportunities, explore current and future technologies and resources, and understand the potential to reduce GHG emissions and material waste.
The expected outcome of the report is to generate actionable knowledge on the use of AM, define recommendations on how to overcome barriers to the adoption and implementation of AM, and suggest materials and products that can be used in the industry in a subsequent phase of the project.

Different methods have been used to map the potential and barriers for the use of AM in the construction industry:

- **Desk research to establish state of the art and identify cases and potential technologies, as well as their barriers and opportunities in Denmark and internationally. The research included scientific articles and publications, reports, and web research. Danish AM Hub team visited relevant national and international industry conferences and projects, where AM has been used, to map successful cases and experiences (Annex A).**
- **Expert interviews, in the format of short semi-structured interviews with a standardised questionnaire. The team conducted 9 interviews with architects, engineers, industry professionals and international experts in innovation and technology (Annex C).**
- **Workshops. Danish AM Hub conduct a series of 6 workshops in collaboration with ConTech Lab - a part of Molio and HD Lab, involving participants with cross-functional competences from the construction industry, academia, and AM technology providers (Annex B).**

The combination of the above-mentioned research approaches provided useful insights into the definition of the recommendations of this study, outlined in the following sections. The lessons learnt will support the implementation of the materials, identifying potential issues and informing further research into improved products to enable short-term value creation.

1. CHALLENGES IN THE CONSTRUCTION INDUSTRY

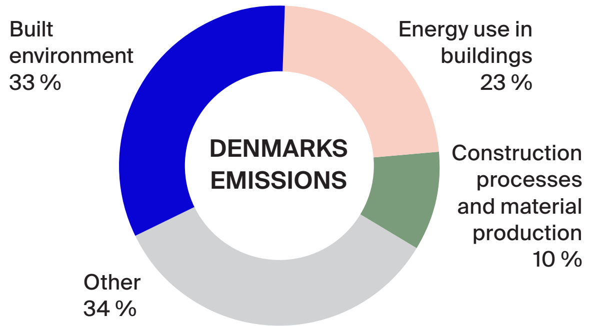
The construction industry is at the forefront of global challenges, particularly in addressing climate change causes and impacts.
This chapter explores critical issues facing the sector such as the impact of building materials, climate resilience and the need for innovative solutions to drive the industry towards a sustainable future.

1.1. Sustainability

The building sector has a significant impact on the climate. Globally, buildings consume 30 percent of energy and contribute 27 percent of operations-related CO2 emissions. Counting emissions from building materials, the sector is responsible for 37 percent of global energy and process-related emissions (United Nations Environment Programme, 2022).

With the world's population expected to grow by 27 percent by 2050 and the building stock set to double, the environmental, social, and economic impact of the built environment will increase significantly (World Green Building Council, 2020).

To achieve the goals of the Paris Agreement, the building sector will need to reach net-zero carbon by 2050, with a 98 percent reduction from 2020 levels and all new buildings being net-zero carbon from 2030 (United Nations Environment Programme, 2022).



In connection with the Paris Agreement, Denmark reported to the United Nations Framework Convention on Climate Change (UNFCCC) 44.7 million tonnes of CO2 equivalent emissions in 2020.

The Danish government's Climate Act has set a target of a 70 per cent reduction in CO2 emissions by 2030 compared to 1990 levels. To achieve this goal, Climate Partnerships were established in 14 sectors, to identify the contribution of each sector. The Climate Partnership for Buildings and Construction identified over 60 areas and presented recommendations that could reduce CO2 emissions by 5.6 megatons per year by 2030, accounting for almost 20 percent of Denmark's overall reduction target (The Danish Housing and Planning Authority, 2021).
In accordance with these efforts, the National Sustainable Building Strategy supports the goal of reducing emissions by 70 percent by 2030. Key strategies to limit the environmental impact of construction include minimisation of energy and resource consumption using renewable energy sources during construction, reduction of material use, and implementation of circular solutions (The Danish Housing and Planning Authority, 2021).

While these strategies represent significant progress, they do not sufficiently consider the Planetary Boundaries, which outline the safe operating space for human activities in nine critical biophysical systems (Rockström, Steffen, Noone, & et al., 2009).

Six of the nine boundaries, including the one for Climate Change, have been exceeded. The planet is now operating in a zone of increased environmental risk.
To move below the Planetary Boundary for "Climate Change", the Reduction Roadmap highlights the urgent need to significantly decrease greenhouse gas (GHG) concentrations in the atmosphere. However, the slow rate of decay of certain GHGs underlines the urgent need for immediate and drastic reductions in emissions (Effekt, MOE, CEBRA, 2022). Current trajectories suggest that the remaining carbon budget to limit warming to 1.5°C will be consumed within five years if emissions continue at current rates.

For the Danish construction sector to effectively contribute to global climate goals, the Reduction Roadmap requires a 95% reduction in emissions by 2035-2040.

This target is significantly more ambitious than the traditional 2050 timeframe, which risks overshooting critical thresholds and exacerbating climate impacts (Effekt, MOE, CEBRA, 2024).

To achieve emission reduction goals and promote climate resilient development, urban systems have a crucial role to play. Cities need to integrate essential elements of adaptation and mitigation into their planning processes, including efficient design, construction, retrofitting, and use of buildings. Successful mitigation involves different stages of construction, including low-emission building materials, efficient building envelope, renewable energy, and recycling practices (Core Writing Team, H. Lee and J. Romero (eds.), 2023).

Multiple barriers, as limited financial resources, the lack of institutional capacity and appropriate governance structures are holding back the decarbonisation of buildings. Energy consumptions and costs for building operation and GHG emissions are affected by building types and their composition. Near zero energy (NZE) or low energy buildings are achievable for both new and retrofitted buildings (Cabeza, et al., 2022).

Most decisions that affect emissions are made before construction begins, in the design phase. The early stages of a project thus offer the greatest potential to influence the emissions over the lifetime of a building (Blanco, Engel, Imhorst, Ribeirinho, & Sjödin, 2021).

Key decisions at the design stage, including whether to retrofit or build new, the size of the building, the level of insulation and the flexibility of the space, can have a significant impact on emissions for decades to come. The transition from low to medium insulation levels often provides a positive cost-benefit ratio. However, a large proportion of Europe's existing buildings are not adequately insulated, and a significant number still use fossil fuels for heating. In EU, almost all buildings constructed before 2010 need to be renovated in order to meet long-term strategic goals (Blanco, Engel, Imhorst, Ribeirinho, & Sjödin, 2021).

1.2. Building process

The construction industry accounts for an estimated 13 per cent of global GDP and has grown at a rate of 6 per cent over the past five years. Due to its massive size, even a small improvement in efficiency and productivity can have a significant impact on the global economy.
Whereas various areas of human life have been transformed by digitalisation and productivity improvements over the past 30 years, the construction industry has lagged behind most other modern industries (Khajavi, et al., 2021).

A McKinsey study estimates that 98 percent of large construction projects experience cost overruns of more than 30 percent. These are often the result of poor cost estimating during the design phase, design change requirements, and payment delays, and can lead to reduced profit margins, material shortages due to insufficient residual budget, and reputation damage for the contractor. In addition, 77 percent of construction projects are delayed by at least 40 percent.

Digital technologies, modularisation, and innovative approaches can play an important role in improving the efficiency of construction processes, and have demonstrated the potential for significant cost savings, shorter project timescales, and reduced environmental impact (McKinsey Productivity Sciences Center, 2015).

Digitisation also plays an important role in cost reduction: utilizing digital Building Information Models (BIM) can streamline project planning and result in durable, long-life cycle buildings (The Danish Housing and Planning Authority, 2021).

Digitalising the building process can allow for wider use of prefabrication and modular construction, resulting in a reduction of material waste by 23-100 percent (United Nations Environment Programme, 2022).

According to the Danish Housing and Planning Authority (2021), prefabricated modular construction offers several advantages that contribute to the rapid, sustainable, and cost-effective development of buildings:

- **Ensure quality and consistency through greater management of both the construction and manufacturing processes.**
- **Reduction of waste and resource consumption by optimising the use of building materials.**
- **Increased potential for recycling and reuse of components.**
- **Increased safety and efficiency in the construction process, improving working conditions.**
- **Flexibility in terms of project schedules and cost effectiveness.**

In Denmark, the construction sector is facing three major challenges: late payments, a shortage of skilled workers, and a low level of innovation activity, with approximately 72 percent of companies in 2020 indicating that they were least likely to innovate, significantly higher than other economic sectors such as manufacturing (42 percent) and infrastructure (59 percent).

In 2021, the Danish government introduced the National Strategy for Sustainable Construction, which aims for more climate-friendly, durable and high-quality, resource-efficient and healthy buildings, as well as digitally enabled construction (European Commission, 2021). The strategy requires the integration of Life Cycle Assessment (LCA) into the building code by 2023. This can provide an example for other countries, highlighting the need to move away from energy efficiency alone to consider the full life cycle emissions of buildings, considering operational as well as embodied carbon (Effekt, MOE, CEBRA, 2022).

Digitalization shouldn't then be seen only as a productivity tool, but there is a need to unlock its potential to integrate sustainable practices, such as embedding LCA into BIM workflows and prefabrication systems for real-time tracking of emissions reductions.

As the impact of climate change on buildings may lead to increased maintenance requirements and associated environmental impacts related to the production, transport, and lifetime of materials, it is necessary to develop multi-functional solutions, technologies, and materials that reduce GHG emissions from the operation of buildings and embodied emissions from the production and processing of building materials (Cabeza, et al., 2022).

1.3. Building materials

Building materials account for a significant proportion of the building sector's climate impact, contributing around 10 percent of global energy-related GHG emissions. The emissions primarily derive from the processing of raw materials for buildings and infrastructure (about 30 percent of total annual construction emissions, mainly from cement and steel) and building operations (about 70 percent) (PEEB Programme for energy efficiency In buildings, 2021).

Once a building is constructed, the emissions associated with building materials are largely irreversible. Considering the typical lifespan of a building (30-130 years), waiting until the end of a product's life cycle to replace it will not be consistent with the 2050 mitigation targets. Therefore, there is considerable opportunity and need to retrofit existing assets (Blanco, Engel, Imhorst, Ribeirinho, & Sjödin, 2021).

The lack of openly accessible repositories of materials production data limits the estimation of emissions (United Nations Environment Programme, 2022). Concrete in particular is the most consumed material in the sector, with its carbon-intensive nature largely due to the use of cement, projected to increase by 12-23 percent by 2050, while steel production is expected to increase by 30 percent over the same period (Langmaack, Scheibstock, Schmuck, & Kraubitz, 2021).

Material re-use has been identified as one of the most promising solutions for reducing GHG in the EU construction sector. An assessment of the environmental savings associated with the re-use of building components has shown that it can reduce the initial embodied carbon emissions by up to 90 percent (Hartwell, Macmillan, & Overend, 2021).

The five main building frames used in construction are: concrete, wood, masonry, steel, and composite. An overview of the cradle-to-gate coefficients for embodied energy and carbon shows that earth materials and wood have the lowest embodied carbon, whereas the highest embodied carbon is found in steel (Cabeza, et al., 2022).

Embodied emissions from the materials production processes account for a significant share of emissions from the buildings sector. Measures to reduce these emissions include improving material efficiency, optimising building design, replacing materials with lower carbon options, improving manufacturing efficiency, recycling waste during the manufacturing process, and reusing or extending the life of building components (Cabeza, et al., 2022).

MATERIALS DEGRADATION:

Climate change, including extreme rainfall events, rising temperatures, and fluctuating heating and cooling demands, has significant impacts on buildings and can affect the durability of construction materials and energy efficiency. The external surfaces of buildings will be exposed to more extreme climatic conditions for longer periods of time, increasing the risk of premature degradation of building components such as roof, wall, and window systems, as well as the risk of water infiltration, leading to moisture-related problems (Lacasse, Gaur, & Moore, 2020).

Concrete is a vital building material and as such it is subject to degradation processes that can be exacerbated by variations in the concentration of CO_2, as well as temperature and humidity, with consequences on the safety, performance and durability of concrete structures (Lacasse, Gaur, & Moore, 2020).

The degradation of materials such as plastics, rubber and wood can be accelerated by increased solar ultraviolet (UV) radiation resulting from factors such as stratospheric ozone depletion and land use patterns, expected to increase with the rise in global temperatures.

In coastal and near-coastal areas, corrosion of metals (carbon steel and zinc) is influenced by the effects of chloride deposition. In Europe, due to future predicted atmospheric conditions, corrosion of exposed metals is expected to increase in coastal areas and decrease inland.

In several European locations, the increasing warming and humidity associated with climate change is predicted to reduce the service life of timber building components. Of particular concern is the increased risk of moisture-related damage to the facades of buildings, as well as the potential for increased vulnerability and deterioration of timber-framed structures (Lacasse, Gaur, & Moore, 2020).

Increasing the resilience of long-lived structures to the impacts of climate change is therefore critical. Life cycle design should address a long-term perspective and consider adaptation to climate change by applying the principles of durability, adaptability, and circularity. The preservation of existing buildings can provide a solution with less environmental impact than replacing them with new constructions, whilst contributing to the preservation and valorisation of the built heritage (European Commission, Directorate- General for Climate Action, 2023).

FAÇADES

Among the building elements, the design and construction of the façade system has a significant impact on a building's operational energy efficiency, accounting for 10 to 30 percent of a building's total embodied carbon emissions, despite its low weight compared to other building components. Improvements in operational performance, indoor comfort and well-being have resulted in the adoption of multi-functional composite façade systems designed to perform well over the lifetime of a building. However, due to the multi-component character and levels of environmental exposure of façade systems, some components experience shorter life spans, resulting in higher turnover rates and embodied carbon emissions (Hartwell, Macmillan, & Overend, 2021).

Limited consideration has been given to the impact of integrating multiple layers and more glued joints on the ability to disassemble and reuse façade components, making it difficult to recover and reuse the elements, impeding design-for-dismantling efforts (Hartwell, Macmillan, & Overend, 2021).

On the contrary, designing modular construction can extend lifespan, allowing disassembly for material recovery at the end of the building's life to maximise the value and reuse potential of the components (United Nations Environment Programme, 2022). Adaptability should be thus supported at the component level to enhance the re-use of components and materials and to facilitate maintenance and refurbishment, and at the building level to accommodate changes in use according to evolving needs (European Commission, 2020).

To increase the sustainability of construction, design decisions should therefore be guided by life cycle analysis based on local data, favouring building materials with performance characteristics appropriate for the local climatic conditions (PEEB Programme for energy efficiency In buildings, 2021).

Low-carbon and low-manufacturing materials should be preferred, rather than CO2-intensive materials such as aluminium or steel, as these require fewer resources for production and are easier to recycle. Choose durable materials that last longer and require less replacement or maintenance and prioritise the reuse of products rather than manufacturing new ones. Local value chains should be encouraged to lower transport emissions and strengthen local economies (PEEB Programme for energy efficiency In buildings, 2021).

1.4. Resources and waste

According to Statistics Denmark, in 2019 the Danish construction sector accounted for 5.0 million tonnes of waste, more than a third of the total waste produced in Denmark. Nearly half of the domestic material use comprises non-metallic minerals, such as stone, gravel and sand extracted for construction activities (European Commission, 2021).

The global consumption of raw materials is expected to almost double by 2060, in particular for minerals and construction materials. Most construction materials depend on energy-intensive extraction processes, leading to negative environmental impacts over their entire life cycle, from loss of biodiversity and water scarcity to increasing carbon emissions. In addition, a significant amount of construction, renovation, and demolition waste is generated globally, around 100 billion tonnes per year, of which 35 percent is landfilled rather than recovered and reused (United Nations Environment Programme, 2022).

The adoption of a circular economy model has the potential to reduce GHG emissions by maximising the useful life of building materials and extending the life cycle of buildings (United Nations Environment Programme, 2022).
The circular economy framework has multiple benefits in terms of both economic returns and environmental sustainability. It focuses on the need to eliminate waste and pollution, increase the life of products and materials, and regenerate rather than degrade natural systems. When applied to the construction industry, such principles offer an effective strategy for achieving global climate goals (The Ellen MacArthur Foundation, 2015).

The global consumption of raw materials is expected to almost double by 2060

Circular approaches to construction enable buildings to serve as repositories of valuable materials that can be reused, decreasing the need for new materials (PEEB Programme for energy efficiency In buildings, 2021). Additionally, the use of local, low carbon materials such as wood, bamboo, clay, stone, and agricultural waste can have a major impact on lowering the construction's embodied carbon emissions. Plant-based biomaterials can act as carbon sinks, capturing carbon over their lifetime, as the living plants absorb carbon from the atmosphere and continue to store it in the building until the materials are biodegraded or incinerated at the end of their life (United Nations Environment Programme, 2022).

The integration of bio-based materials into the construction industry marks a significant step towards sustainability, offering both environmental and functional advantages. Sourced from renewable materials such as plants, algae, and microorganisms, bio-based materials provide alternatives to conventional materials that are often resource-intensive and emit high levels of carbon dioxide during production. These materials are often biodegradable or recyclable, and can enhance indoor air quality, contributing to healthier building environments.

The use of biogenic materials such as wood, straw, eelgrass, and hemp represents an essential strategy to align construction practices with Planetary Boundaries, reducing GHG-emissions while regenerating natural systems. This regenerative approach aligns with the "safe operating space" concept, essential for maintaining climate stability and biodiversity (Effekt, MOE, CEBRA, 2022) (Effekt, MOE, CEBRA, 2024).

A new systems approach is then needed, based on:

- **Designing more efficiently to build with less.**
- **Using alternative building materials and decarbonising conventional ones.**
- **Renovating existing buildings rather than developing new ones.**
- **Mixing and optimising uses and designing components for disassembly and reuse.**
- **Choosing locations which require less materials, foundations, and transport.**

(PEEB Programme for energy efficiency In buildings, 2021)

An in-depth analysis of the environmental impact of innovative construction methods in the context of circular economy principles can be performed using Life Cycle Assessment (LCA). Designed to measure the environmental footprint of buildings, LCA evaluates processes, materials and energy use over the entire life cycle of a structure. This approach is crucial in examining the environmental impact of different construction techniques, energy strategies, components and products. The scope of LCA covers both new construction and renovation projects, providing insight into minimising resource consumption and limiting air, water and soil pollution at every stage of a building's life. To integrate LCA into construction practice seamlessly, it is essential to embed LCA databases and analysis routines into widely used simulation tools such as energy performance simulation and Building Information Modelling (BIM). This integration has a significant influence on the design efficiency and climate impact reduction of the construction industry in the context of the circular economy. Adopting a life-cycle approach provides building owners and designers with comprehensive information that enables them to make environmentally conscious decisions. This method facilitates the optimisation of solutions with respect to different environmental concerns, geographical locations, and temporal aspects of environmental impacts. In addition, the use of a consistent methodology ensures accurate reporting of critical environmental indicators, such as CO_2 emissions and energy demand, throughout a building's lifecycle.

Adopting circular principles in construction is thus an effective strategy for aligning with global climate goals, offering economic returns while promoting environmental sustainability.

1.5. Conclusion

There is an undeniable imperative to change the path of the construction industry as both a major contributor to climate change and a key player in developing solutions for a sustainable and resilient future. From the urgent need for sustainable practices to the critical role of digitalisation and innovative materials, the path to a net-zero carbon future requires a systemic transformation.

Decisions made in the early stages of a project, particularly during the design phase, have an unparalleled impact on building's life cycle emissions.

Adopting modularity, digitalisation, and adaptability at different levels can extend the life of components, promote sustainability, and reduce material waste, offering benefits such as enhanced quality, resource optimisation, recycling potential, and improved construction efficiency.

To address the challenges posed by climate-induced degradation of materials, particularly concrete, and building components, a strategic focus on life cycle design, adaptation principles and the use of sustainable, locally appropriate materials is crucial for the long-term sustainability and resilience of structures. Potential synergies between modular construction, biogenic materials, and circular economy principles need to be explored to achieve regenerative outcomes.

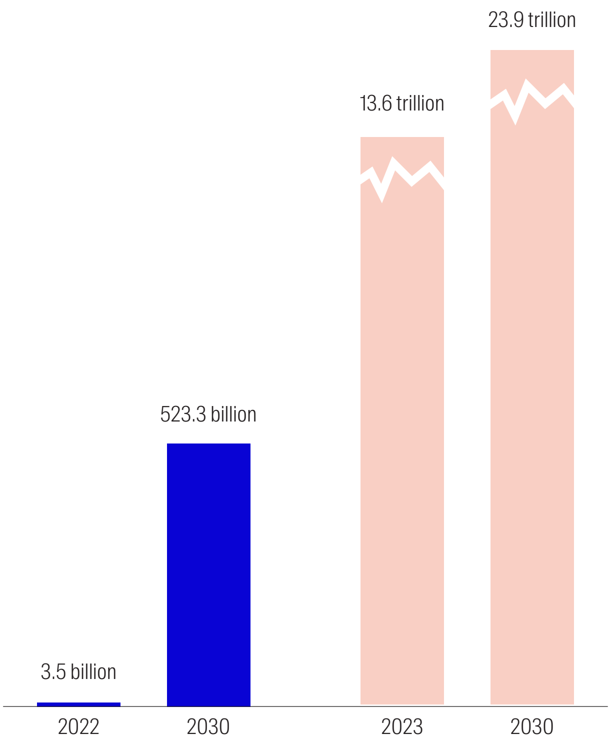
Potential synergies between modular construction, biogenic materials, and circular economy principles need to be explored

With the aim of addressing the challenges described above, the next chapter explores the potential of additive manufacturing, introducing and analysing its role in transforming construction practices and further contributing to ongoing efforts towards sustainable, resilient, and low-carbon building solutions.

2. AM IN CONSTRUCTION

Additive Manufacturing (AM), which emerged in the 1980s as a polymer prototyping technique, revolutionised traditional manufacturing by introducing a layer-by-layer approach that adds material rather than subtracting it. Unlike conventional manufacturing, AM is tool-independent, making the process much faster, especially in the early stages of production, and offers unparalleled design flexibility, automation, digitisation benefits and high precision. Large-scale 3D printing has been shown to efficiently produce new geometries, opening new horizons for construction applications (Khajavi, et al., 2021).

The market for 3D printing in construction is forecast to grow from around USD 3.5 billion in 2022 to around USD 523.3 billion in 2030, with a compound annual growth rate (CAGR) of around 87 per cent (Zion Market Research, 2023). For comparison, the global construction market reached a value of around USD 13.57 trillion in 2023, and it is estimated that will continue to grow at a CAGR of 6.5 per cent between 2024 and 2032, to reach a value of approximately USD 23.92 trillion (Expert Market Research, 2023).



By analysing the key benefits and challenges associated with the use of AM, the barriers to adoption, and the reasons for the primary focus on concrete, this chapter attempts to provide viable solutions to the construction industry challenges presented in section 1.

2.1. Sustainability

Existing literature on AM in construction tends to focus on environmental impacts, while economic and social considerations are often neglected. Research encompassing all three pillars of sustainability - environmental, economic, and social - is necessary for a comprehensive understanding of sustainable practices (Ibrahim, Eltarabishi, Abdalla, & Abdallah, 2022).

Research encompassing all three pillars of sustainability ... is necessary

This section presents a combined assessment to provide a holistic understanding of the impact of 3D printing in construction.

ENVIRONMENTAL SUSTAINABILITY

AM can contribute to a significant reduction of GHG emissions through:

- **Material efficiency: Precise and targeted material usage, optimising materials and resource efficiency, reduced material consumption and demand for raw materials.**
- **Waste reduction: Recycled materials, materials derived from construction and demolition waste, and application in renovation minimizes the need for new construction extending the lifespan of buildings and reducing waste generation.**
- **Sustainable materials: Use of bio-based or recycled materials.**
- **Energy savings: Reduced material extraction, on-site 3D printing reduce transport emissions by producing parts directly at the construction site, the layer-by-layer deposition process eliminates the need for complex formwork.**
- **Production efficiency: Enabled design complexity allows for more resource-efficient structures and systems.**
- **Lower carbon emissions: Improved material efficiency and reduced energy consumption, reduced transportation-related emissions.**
- **Water conservation: Materials that require less water for construction.**

(Ibrahim, Eltarabishi, Abdalla, & Abdallah, 2022)

I AM MSHRM

A project developed by Danish AM Hub and Bjarke Ingels Group (BIG), is an example of how the combination of 3D printing and bio-based materials can promote environmental sustainability. The building consists of 3D- printed frames made of recycled plastic and baked mycelium. The frames can be easily produced, assembled, disassembled, reassembled or recycled after use.

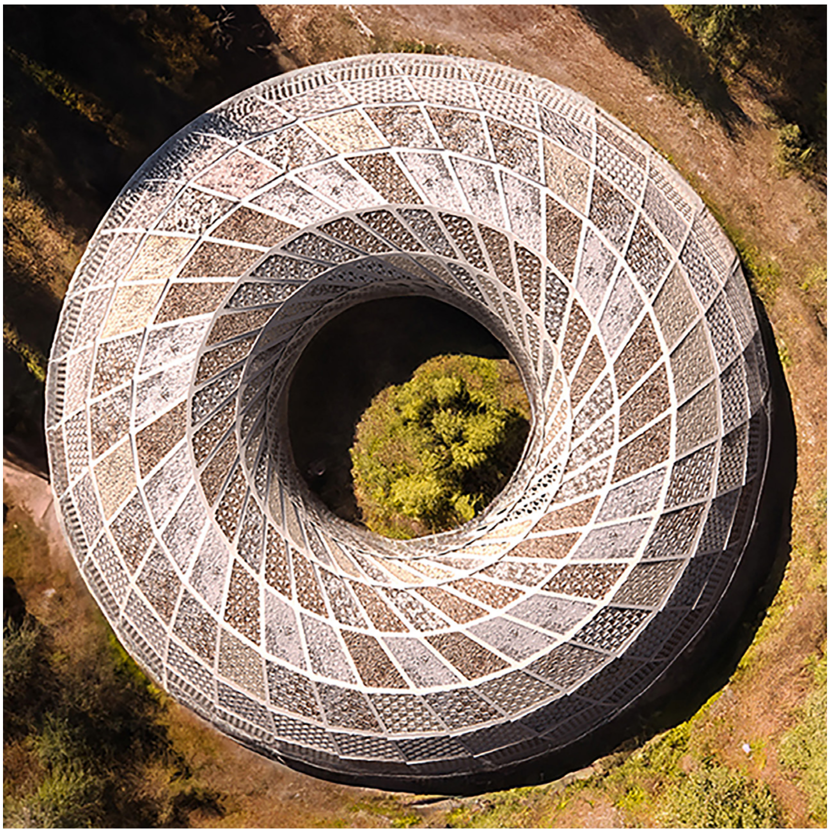


Figure 2/3 - I AM MSHRM, Danish AM Hub & Bjarke Ingels Group (BIG) - Annex A, Case study 001, Image: Bjarke Ingels Group (BIG)

ECONOMIC SUSTAINABILITY

Thanks to robotic technology capable of continuous operation, AM reduces construction time and increases productivity, resulting in significant cost savings. The use of diverse materials and reduced waste also contribute to the economic benefits. However, challenges such as the cost of transporting and installing printers and limited suppliers of compatible materials can affect overall cost- effectiveness (Ibrahim, Eltarabishi, Abdalla, & Abdallah, 2022).

The economic sustainability of the use of AM in construction is highlighted by several key drivers. During the workshop series, it has been discussed the role of design optimisation: the implementation of complex and intricate designs leads to the creation of resource-efficient structures and systems, promoting a more sustainable use of materials. In addition, the ability to manufacture customised components on-site in renovation and retrofit projects could improve economic performance by minimising waste and streamlining construction processes. The increased productivity and flexibility offered by AM further contributes to economic sustainability, as faster construction times, local production, reduced inventory requirements, less rework and adaptable schedules all contribute to the cost-effectiveness of the project.

Figure 4 - reMARBL3D, ETH, Digital Building Technologies – Annex A, Case study 002

As highlighted in one of the expert interviews, 3D printing offers sustainable and cost-effective advantages as its additive nature minimises material waste, making it a more resource-efficient alternative.

SOCIAL SUSTAINABILITY

The construction industry is notorious for its high rate of workplace injuries. The potential of AM to automate construction processes, reducing manual labour and improving workplace safety, aligns with the industry's shift towards safer, more efficient practices (Paolini, Kollmannsberger, & Rank, 2019). Workers trained to operate 3D printers can perform their tasks more efficiently, reducing the likelihood of injuries on site (Ghaffar, Corker, & Fana, 2018).

AM ability to offer customised products strengthens the relationship between designers and customers, increasing satisfaction. AM can provide sustainable homes and cities at a reasonable cost, with a smaller environmental footprint and a positive social impact, in alignment with the United Nations Sustainable Development Goals (SDGs) (Ibrahim, Eltarabishi, Abdalla, & Abdallah, 2022).

This technology not only improves construction efficiency but also offers design flexibility, signalling the transformative potential for automation and socio-economic benefits in the ongoing digital transformation of industry (Khajavi, et al., 2021).

3D printing offers transformative potential for achieving sustainability and circularity in construction. According to some of the experts interviewed, integrating nature-based solutions into building designs, such as embedding air and water flow systems, demonstrates a holistic approach to sustainable architecture. In addition, they underlined the importance of engaging with local cultures and architectural traditions in 3D printing projects.

For example, the work of the Institute for Advanced Architecture of Catalonia (IAAC) explores how vernacular design principles can inform digital fabrication to create culturally responsive structures. This approach not only digitises traditional techniques, but also fosters collaboration between researchers, industry and local communities. By embedding social and environmental values into their designs, it could be possible to create an inclusive building ecosystem that seamlessly integrates new technologies with cultural and environmental contexts.

Figure 5 Tova, 3d-printed Earth Architecture, IAAC - Annex A, Case study 003, image: Gregori Civera

2.2. Building process

INNOVATION

In the face of global challenges, innovation and technology are key to delivering cost-effective solutions (Chamley, 2019). The use of AM in the construction industry represents a significant innovation, using robotics and process automation to improve productivity, quality control and working conditions, while addressing skills shortages. AM is in line with the principles of Industry 4.0, offering benefits such as customisation, flexibility, design complexity and reduced transport costs (Ghaffar, Corker, & Fana, 2018).

...democratise architecture by directly connecting communities with fabrication tools

One of the interviewees highlighted the potential of online platforms and 3D printing to democratise architecture by directly connecting communities with fabrication tools.
Whilst architects and designers often seek circular and tailored solutions, AM not only facilitates these goals, but also enables designers to commercialise innovative products. This approach promotes revenue-sharing opportunities and encourages cross-disciplinary collaboration in the design process.

DIGITAL TECHNOLOGIES

The 3D printing digital workflow begins with the creation of a 3D model using computer-aided design (CAD) software. This model can be developed manually or through highly automated processes such as topology optimisation. Following the design phase, the CAD model is converted into a format suitable for 3D printing. During process planning, the geometric model is positioned in the build space, support structures are added as required and the model is sliced into layers. The toolpath is then generated, and process parameters selected before being translated into machine language for the numerical control of the 3D printer (Paolini, Kollmannsberger, & Rank, 2019).

Digital technologies such as Building Information Modelling (BIM), robots, drones, 3D scanning, sensors and the Internet of Things (IoT) are reshaping the construction landscape. BIM supports decision-making in the early design phase and evaluates design options, considering embodied emissions. Combining 3D printing with robotics through automated prefabricated buildings increases productivity. Drones facilitate real-time monitoring and inspection of construction projects, while sensors and IoT enable continuous data collection, monitoring, and preventive maintenance (Cabeza, et al., 2022).

In the design phase, AM can contribute significantly to the digitisation of construction processes by creating a data-sharing platform that integrates printing software, BIM and collaboration between clients and designers, enabling the production of customised components with low production costs and high efficiency for personalised designs.

While BIM provides critical data support for AM by providing accurate spatial positioning information, enabling high-precision printing of buildings and the automation of design processes, AM contributes to optimising topology and maximising functionality with minimal material use by modifying shapes and structures (Xie, Xin, Wang, & Xiao, 2023). However, the integration of AM parts into BIM requires careful consideration of geometric and material representation to avoid design limitations (Paolini, Kollmannsberger, & Rank, 2019).

The significant potential of AM in construction lies in its seamless integration within the digital design framework. As articulated in an expert interview, the connection between AM and digital tools facilitates a cohesive transition from design to fabrication, providing a more efficient and consistent approach to construction processes. The link between AM and digital tools enhances the synergy within the unique design-to-manufacture format, demonstrating the promise of efficient and integrated construction processes.

Figure 6 HIVE Project, Ye Sul E. Cho, Ji Shi, Meghan Taylor, James Clarke-Hicks, Isabel Ochoa and David Correa, University of Waterloo and SDI Design - Annex A, Case study 004, Image: Shabaan Khokhar

Interviewees also agreed that knowledge sharing and collaboration between computation and engineering can bring new perspectives to AM and its applications, pushing the boundaries of traditional practices. New technologies can also play a key role in reshaping industry norms. As more people gain access to technology, there could be an increase in innovative shapes and materials that are not bound by past knowledge.

COMPARATIVE LIFE CYCLE ASSESSMENT (LCA) OF 3D PRINTED AND CONVENTIONAL CONSTRUCTION

This subsection offers a focused analysis of the environmental and material efficiencies achieved through 3D printing, tying directly to the broader discussion of building processes and their optimization via AM technology.

Figure 7 Hexastone, Design for disassembly, Technische Hochschule Lübeck, Vertico, Sika – Annex A, Case study 005, Image courtesy of Technische Hochschule Lübeck

An example of LCA of 3D printed houses, based on a 60 m^2 terraced house as a functional unit, shows a significant reduction in environmental impacts compared to conventional construction methods. In most impact categories, 3D printing shows superior performance. In particular, the study shows reduced material use, which contributes to a 75-80% lower environmental impact in categories such as human health, ecosystem quality, climate change and resource depletion. However, specific materials - wood floorboards, window frames, and Portland cement, contribute significantly to the climate impact of 3D printing. In contrast, conventional buildings use larger quantities of materials and generate higher GHG emissions, demonstrating the material efficiency and environmental benefits of AM (Ali, 2019).

A study focused on the LCA of 3D printed bio-based homes using wood flour-filled polylactic acid (PLA) and wood fibre insulation shows significant environmental advantages over traditional wood frame houses: 3D printed homes produce approximately half the global warming potential compared to conventional stick-built homes for an 84 m^2 structure with a 50-year lifespan. These savings are attributed to reduced material use, waste minimisation and the use of bio-based, biodegradable materials, and improved energy efficiency (Liedtka, 2022).

DESIGN

Traditional construction methods often struggle to accommodate design changes, causing delays and complications. AM optimises production and assembly processes, introducing new aesthetics, materials and complex shapes that were previously difficult to achieve (Cabeza, et al., 2022). Compared to traditional manufacturing methods, AM offers unique features, including increased geometric freedom, reduced material waste, less reliance on human labour, and lower manufacturing costs and times (Xie, Xin, Wang, & Xiao, 2023).

Figure 8 Ecoalf store, Nagami - Annex A, Case study 006, Image: Alfonso Quiroga

This flexibility allows architects and construction teams to adjust seamlessly, reducing the problems associated with design changes, and increasing the overall efficiency of construction projects (Ghaffar, Corker, & Fana, 2018). Numerical methods, including size and shape optimisation, play a crucial role at this stage to ensure that the final design meets the functional and structural requirements (Paolini, Kollmannsberger, & Rank, 2019).

Biopolymer composites offer an interesting case for bio-based circular design in construction. They consist of a binder mixed in a solvent and reinforced with fibres and fillers to form a composite that is 100% biodegradable and can be produced on a large scale. This offers new unique opportunities for material design and control that are not feasible with conventional materials (Nicholas, et al., 2023).

AM optimises production and assembly processes

An example of the use of a biopolymer composite material reinforced with different types of cellulose from agricultural and other waste streams is Radicant, a customised interior wall panelling system.
With an average lifespan of less than 10 years and only 20-30% of elements recycled or reused, interior finishing is a short-lived construct. This 3D-printed biopolymer composite instead shows continuous behaviour throughout the manufacturing process and usage, reacting to changes in heat and humidity in the exhibition environment, and it is easy to repair thanks to the biopolymer's adhesive properties. The panelling system can be divided into smaller pieces and recycled at the end of its life, 3D printing a new object (Nicholas, et al., 2023).

Figure 9 Radicant, Royal Danish Academy, CITA, DTU - Annex A, Case study 007, Image courtesy of Centre for Information Technology and Architecture (CITA)

In the field of interior design, the transformative impact of AM is demonstrated by its ability to address significant challenges. Expert feedback highlighted that the traditional approach of tailoring designs to specific locations often results in significant material waste, with approximately 25% of construction materials being discarded due to customisation requirements. By adopting a customised, on- demand 3D printing model, the waste can be significantly reduced by eliminating the need for excess stock and enabling efficient use of materials. In addition, the technology allows materials to be recycled and reused, providing an environmentally friendly solution for transforming waste into new and tailored interior design elements. This paradigm shift in design and production not only minimises environmental impact, but also offers opportunities for collaborative development and market exploration, demonstrating the multiple benefits of AM in interior design.

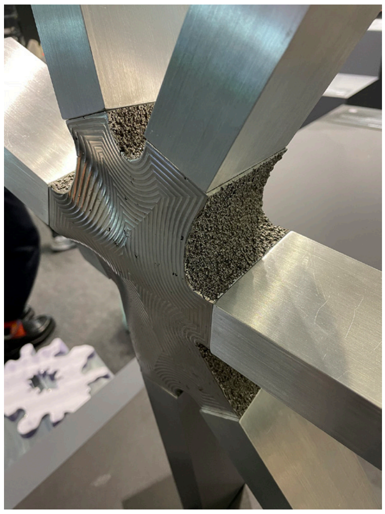
Figure 10 3D printed film studio, Casinos Austria & Austrian Lotteries Group – Annex A, Case study 008, Image courtesy of Philipp Aduatz

SPECIAL ELEMENTS

The design freedom offered by AM goes beyond geometric complexity. By manipulating and varying the raw materials during the printing process, functionally graded materials can be achieved, increasing strength in specific areas that are subject to higher loads. Further testing, standardisation and the development of reliable simulation models are essential to fully realise the potential of AM in construction and to derive product properties based on feedstock, printing process and parameters (Paolini, Kollmannsberger, & Rank, 2019).

A transformative technique within AM is the modification of material properties, such as the incorporation of lightweight aggregates into the AM material. This not only improves structural properties, but also enables the creation of intricate internal patterns, demonstrating its flexibility in meeting diverse design requirements (Briels, et al., 2023).

Figure 11 InNoFa-Demonstrator, Individual node facades, FLEX Research Group, HTWK Leipzig - Annex A, Case study 009



According to one of the experts interviewed, the general advantage of AM is that complex geometries can be achieved very quickly, a process that is labour-intensive and challenging with traditional methods such as casting, especially in the context of concrete structures. AM allows greater control over inhomogeneous materials, enabling the incorporation of different property gradients or mechanical properties within a single part, with great potential to create unique and specialised structures. This capability has significant implications for the creation of innovative, functional designs tailored to specific architectural needs.

SUPPLY CHAIN

AM can impact supply chains reducing the number of suppliers by eliminating the need for assembly operations, leading to improved logistics efficiency and reduced demand for semi-finished goods and inventory. Furthermore, it may reduce product delivery times and reform traditional warehousing and transportation models. Finally, AM can increase production and distribution flexibility, enabling customer participation in design and production, and product customisation. The technology's production flexibility allows components to be manufactured on demand, reducing the need for large inventories and associated costs (Xie, Xin, Wang, & Xiao, 2023). Components can be produced in a factory, transported to the construction site, and then assembled and finished on site (Khajavi, et al., 2021). AM allows also decentralised supply chain for construction with on-site 3D printing, where the printer is transported to the site and manoeuvred as needed until construction is complete (Khajavi, et al., 2021).

Efficient and flexible manufacturing and supply chain management has therefore become an integral part of 3D printing production processes. AM management process involves the coordination of various elements, including the robotic platform, a power distribution substation, design software and the print nozzle (Guamán-Rivera, et al., 2022).

BARRIERS TO ADOPTION

Expert interviews identified a significant resistance to change within the industry, often attributed to an older generation of professionals who lack familiarity with computer-aided design (CAD) methods. Re-skilling the workforce to operate advanced technologies, such as 3D printing, remains a considerable obstacle. One expert in 3D printing emphasized the prohibitive costs of initial equipment investments, coupled with the absence of standardized training programs in university curricula.
Smaller architectural firms were also noted as being particularly disadvantaged, often lacking the financial resources to invest in computational design tools. As a result, graduates equipped with advanced digital design skills face underutilization in a sector that struggles to integrate these capabilities effectively.

A further challenge lies in the absence of industry-wide standards for 3D printing, which complicates its adoption into established workflows. Experts stressed the importance of aligning AM innovations with regulatory frameworks to ensure compliance and facilitate broader acceptance. Progress in achieving certifications, such as fire retardancy for 3D-printed components, demonstrates the ability of AM technologies to meet performance and safety standards without compromising their innovative potential. Nevertheless, regulatory approval processes and lingering doubts regarding the reliability of 3D printing as a legitimate construction method continue to hinder its scalability.

Additionally, resistance to fully 3D-printed housing persists, driven by aesthetic preferences and environmental concerns over material sustainability. One expert highlighted the importance of addressing these perceptions through education, standardization, and collaboration across industry stakeholders.

Despite these barriers, experts recognize the significant opportunities AM presents for creating bespoke architectural components, particularly those featuring intricate geometries and complex details that are challenging to achieve using conventional methods.
AM offers a compelling approach to customization, facilitating the design and production of unique components that not only enrich architectural expression but also underscore the transformative potential of personalized solutions within the construction industry.

2.3. Building materials and elements

The pursuit of net-zero carbon buildings requires a re-evaluation of fundamental principles and the reduction of emissions in the materials production process. This includes optimising design and materials (Blanco, Engel, Imhorst, Ribeirinho, & Sjödin, 2021).
Digital buildings are designed, validated, and optimised in the design phase, where construction becomes an integral part of the design. Therefore, environmental criteria need to be integrated into the design phase (Agustí-Juan & Habert, 2017). The material efficiency achieved through 3D printing can significantly reduce GHG emissions (C40 Cities, ARUP, University of Leeds, 2019).

CEMENTITIOUS MATERIALS

- 3D printed concrete: Fundamental material for 3D printing in construction, it is optimised for extrudability, buildability and open time, essential concepts in 3D printing. To meet rheological requirements, coarse aggregates are often replaced by fine aggregates such as sand, clay, fly ash and silica fume. However, the absence of coarse aggregates makes the concrete susceptible to shrinkage, prompting research into solutions such as glass fibre or shrinkage-reducing additives.
- 3D printed geopolymer: Innovative material that offers an alternative to traditional cement concrete, and shows potential in terms of sustainability and durability.
- Fibre-reinforced 3D printed concrete: Incorporating fibres into 3D printed concrete improves its mechanical properties, contributing to increased strength and crack resistance.
- Fast curing 3D printed material: Responding to the need for rapid construction, focuses on achieving fast setting and early strength development, although careful consideration is required to manage heat generation during hydration.
- Earth-based 3D printed material: Environmentally friendly option for 3D printing, in line with sustainable construction practices.
  (Puzatova, Shakor, Laghi, & Dmitrieva, 2022)

CONCRETE

Compared to the traditional cast-in-place methods, 3D printing eliminates the need for formwork, allowing complex structures to be built faster and with less on-site labour (Han, Yang, Ding, & Xiao, 2021). Two major construction strategies have been identified in the context of concrete 3D printing, mass and reinforced concrete. Mass concrete walls, designed primarily for compression resistance in low-risk areas, feature superimposed cords with occasional curves and parallel lines, often filled with different materials. The wall thickness is increased for lateral stability and thermal or acoustic insulation. It should be noted that there are no general strategies for adaptability or compliance with building codes. The second strategy uses steel reinforcements to achieve higher performance and larger structures. Examples include horizontal meshes, vertical reinforcing bars and the use of mixtures on steel meshes. The size of the printing system, which limits the dimensions of the elements to be built and the capacity to print a complete building or to execute it in parts, is another important factor in the construction strategy. The printing speed affects the mechanical resistance of the components to be printed, which means that constructing and assembling them in smaller pieces may be the most optimal method (Guamán-Rivera, et al., 2022).

Figure 12: The Wave House Data Center – The first and globally largest

industrial building made with 3D construction printing technology, built by PERI 3D Construction using COBOD technology - Annex A, Case study 010, Image courtesy of COBOD

The use of geopolymer/alkali-activated materials, known for their ecological benefits and ability to incorporate solid waste with minimal environmental impact, could provide a potential environmental benefit as a replacement for conventional Portland cement (PC) in 3D printing. A LCA of the environmental impact of 3D printed structures using newly developed construction and demolition waste (CDW)-based geopolymer materials shows a reduction in waste and improved environmental performance, particularly in terms of global warming potential and fossil fuel deposition, for the geopolymer-based 3D printed structures. The incorporation of renewable energy sources in the production of CDW-based geopolymer systems could further enhance their environmental sustainability (Khan, et al., 2023).

During the expert interviews, particular emphasis was placed on the potential for optimising structures, leading to a reduction in the amount of material used while achieving more stable and stronger structures. A common practice in the construction industry is to oversize structures for safety reasons, resulting in the use of more material than necessary, and AM can be a way to address this issue by introducing concepts such as topology optimised structures and generative design.

THE ENVELOPE - FACADES

As the critical barrier between the indoor and outdoor environments, the building envelope has primary responsibility for managing a range of building physics requirements, including heat, moisture, airtightness, sound, and light. Traditional approaches to the construction of building envelopes include solid constructions, which integrate all requirements into a single element, and layered

Figure 13 3DLightBeam+ robotic 3D Concrete Printing - Stress-based design for 3D concrete printed horizontal structures, Luca Breseghello, CREATE SDU - Annex A, Case study 011

constructions, where different layers address individual requirements. While solid structures, such as hollow bricks or lightweight concrete, offer simplicity in meeting multiple requirements, they are limited in optimising individual functions or adaptability. On the other hand, multi-layered facades, such as ventilated facades, allow functional optimisation but introduce complexity, potential for failure and poor recyclability, particularly in the case of external thermal insulation composite systems. In response to these challenges, there is a growing desire to integrate, hybridise and optimise building functions into building components without the drawbacks associated with traditional methods. AM is emerging as an important solution in this context (Briels, et al., 2023).
With its innovative design approach, AM offers significant potential, particularly for façade elements, excluding the requirement for multiple layers and materials, promoting recyclability, and significantly reducing the number of steps and interdependencies between different construction disciplines on site (Briels, et al., 2023).

The critical role of the building envelope in maintaining indoor environmental quality (IEQ), particularly through thermal regulation, emphasises the importance of improving the thermal performance of façade elements. While the façade contributes approximately 20 per cent of the transmission heat losses responsible for the heating energy demand of buildings, the use of AM in this context can lead to significant energy savings and reductions in operational carbon emissions. Despite the growing interest in

Figure 14 Tiffany façade, MVRDV, Aectual, BUROMILAN – Annex A, Case study 012, Image: MVRDV

AM, empirical studies of the thermal performance of AM elements require further investigation, particularly in the design and evaluation of the thermal characteristics of monolithic AM façade elements. Existing research reveals a notable gap in the comparative analysis of different AM processes, materials, and strategies to improve the thermal performance of these elements (Briels, et al., 2023).

Figure 15 Ceramic House, Studio Rap - Annex A, Case study 013, Image: Riccardo De Vecchi

2.4. Resources and waste

The incorporation of AM technology into the construction industry can have a significant impact by using waste-based materials, particularly those derived from construction and demolition waste (CDW). This not only helps to reduce the environmental impact of construction but is also in line with the principles of a circular economy, where waste materials are reused rather than discarded (Khan, et al., 2023).

3D printing's accuracy in material usage can lead to a significant reduction in waste on construction sites and to the optimisation of resource utilization. In addition, the elimination of the need to purchase excess materials leads to cost savings in both procurement and storage (Ghaffar, Corker, & Fana, 2018).

Figure 16 Wohn Homes - Annex A, Case study 014, Image courtesy of Wohn Homes

The environmental benefits of the technology were a common theme in interviews with experts in architecture and 3D printing: For example, accurate 3D modelling can reduce the amount of concrete used in construction.
3D printing uses less material overall, while allowing more complex structures to be built with less skill. Experts also highlighted the role of clay and novel composites in reducing CO2 emissions and achieving cost efficiencies in both new construction and renovation. Taken together, these findings underline the role of AM in optimising material use and supporting sustainable practices.

BIOMATERIALS

In response to increasing efforts within the architecture and construction industry to move towards a circular bio-economy, there is growing interest in regenerative bio-based materials. They could replace more carbon-intensive materials and offer the opportunity to diversify conventional building materials by introducing innovative and distinctive functionalities.
As the biodegradability feature does not make them as durable as conventional fossil-based materials, embedding self-adaptation and maintenance capabilities into biopolymer composites and 3D printed bio-based architectural elements would significantly increase their application possibilities in architecture. This would reduce maintenance and repair costs, particularly in facades and panel elements, while maintaining the fundamental benefits of a fully biodegradable material.
3D printed architectural elements manufactured from bio-based materials can adapt to environmental changes and perform better over time, according to their local orientation and exposure (Hoenerloh, Nicholas, & Sonne, 2024).

3D printing thus provides a complementary technology for increasing use of biobased materials by optimizing material efficiency and enabling complex construction that can significantly reduce emissions over a building's lifetime. According to the experts interviewed, 3D printing's ability to produce complex geometries also supports the creation of ecologically sensitive designs, enabling the creation of hyper-specialised forms that are beneficial to biodiversity and biophilic design, for example.

Despite these advantages, several challenges hinder the large-scale adoption of bio-based materials and 3D printing in construction. For instance, current building regulations often do not account for the unique properties of bio-based materials, creating a need for updated standards that ensure safety and performance compliance. Similarly, scalability remains a concern as the production and sourcing of bio-based inputs need to expand sustainably without negatively impacting food security or natural ecosystems (Effekt, MOE, CEBRA, 2024).

Figure 17 The eggshell project, Manufactura - Annex A, Case study 015, Image: Arturo Arrieta

The adoption of bio-based materials must be accompanied by broader systemic changes to reduce the building industry's overall environmental footprint. These include shifting from net-zero targets to regenerative models that not only mitigate harm but actively restore ecosystems. The focus should shift to maximising the efficiency of available resources and incorporating "deep circularity", which addresses consumption without further resource depletion, as the building industry implements new technologies (Effekt, MOE, CEBRA, 2024).

In this context, the integration of bio-based materials and AM could serve as a cornerstone for creating buildings that operate within the Earth's biophysical limits, meeting both climate goals and societal needs for sustainable housing and infrastructure.

By leveraging the inherent synergy between bio-based materials and AM, the construction industry can pioneer a transformative shift towards a regenerative future, balancing functionality, sustainability, and ecological integrity.

Over the next decade, one expert interviewed foresees a shift in design language driven by AM, as decision-makers more familiar with the technology come forward. This evolution could drive sustainable innovation, with 3D printing supporting the integration of living materials and biodesign.

Figure 18 3DNATURDRUCK, Biocomposite Reciprocal Canopy, BioMat Department, University of Stuttgart - Annex A, Case study 016

LOCAL MATERIALS AND EARTH-BASED MATERIALS

Figure 19 'To Grow a Building' - Annex A, Case study 017, Image: Nof Nathansohn

The use of local materials, particularly clay, in construction presents both challenges and opportunities. Interviewees highlighted the potential of clay 3D printing, which not only has environmental benefits, with potential CO_2 savings of around 90% compared to a conventional construction, but also offers the prospect of economic viability as the technology develops.
The dynamic nature of local materials, influenced by factors such as moisture and composition, requires innovative solutions in material development and machine adaptation.

In addition, earth-based materials offer considerable transportation and sustainability benefits, as they can be extracted and processed on site. The materials were used in traditional architectural methods that allow for the construction of sustainable, healthy and thermally efficient buildings, but involved a significant amount of skill and manual labour - challenges that 3D printing technology could address (Chadha, et al., 2024).

Figure 20 Tecla, WASP + Mario Cucinella Architects - Annex A, Case study 018, Image WASP

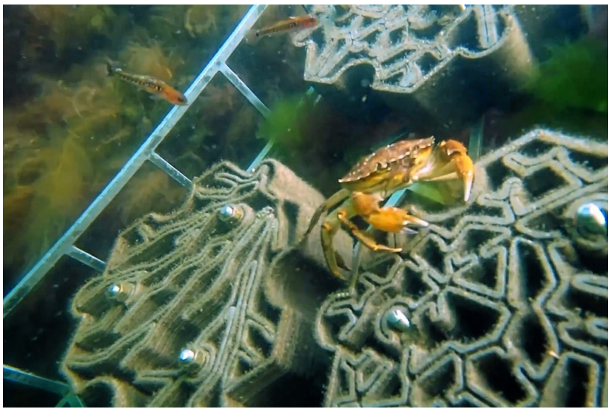


Figure 21 ReefKasse system, Reef Circular - Annex A, Case study 019, Image: Anemo Robotics

precision. Experts interviewed explained that using earth as a print material introduces variability due to factors such as humidity and soil composition, which can vary significantly even within the same site. Overcoming these challenges involves human-machine collaboration and the integration of AI and sensors to dynamically adapt machines to changing material conditions. In addition, the construction industry's demand for large-scale, low-cost materials presents barriers for 3D printing to overcome in order to become economically viable.

FUTURE OPPORTUNITIES

The interviews highlighted that the transition from experimental research to industrial application involves not only technological refinement, but also the adaptation of design processes to the unique constraints and opportunities of 3D printing. This ongoing evolution underscores the need for an ecosystem in which AM innovations are integrated into broader construction workflows and markets.

Looking to the future, interviewed professionals expect that the integration of AI with 3D printing will streamline design processes and allow for more complex geometries and materials. AI and AM can work together to create optimised, sustainable structures. Other experts suggested that open-sourcing of 3D printing technology could accelerate innovation, particularly in regions where labour costs and resource scarcity differ significantly. These forward-looking perspectives highlight the transformative potential of 3D printing to reshape global construction practices.

Figure 22Airlements, Insulated Walls with Sustainable Mineral Foam, FenX, ETH Zürich – Annex A, Case Study 020, Image: Patrick Bedarf, Digital Building Technologies, ETH Zurich

2.5. ANALYSIS

The comprehensive analysis of expert interviews, workshop results and 20 case studies, representative of different materials, system flexibility and building typologies, has revealed both challenges and significant potential for sustainable improvements:

These learning points highlight the critical importance of continued research, technological development and knowledge dissemination to bridge the existing gaps and fully utilise the potential of AM for sustainable construction practices.

- **There is an interest in AM for construction, but limited knowledge of technology, potential and use.**
- **AM is mainly known as a structural onsite concrete solution or for experimental designs and small scale.**
- **The documentation and sustainability aspects of AM need to be further explored to be able to scale AM in construction.**

Key challenges in the construction sector have been identified in:

	CHALLENGES	POSSIBLE AM BENEFITS
MATERIALS EMISSION	Production and waste Use of raw materials Lack of materials repositories	Reduction waste and resource consumption Sustainable materials Circularity
MATERIALS DEGRADATION	Climate change (extreme weather conditions) Durability, adaptability External surfaces	Resource-efficient structures and systems Retrofitting
MAINTENANCE	New buildings VS retrofitting Lifespan Lack of digitalisation	Integration with digitalisation – BIM Integration LCA in the design phase
LAYERED CONSTRUCTIONS	Poor recyclability Lifespan components Mechanical properties	Design for disassembling Modular construction Adaptability
THERMAL INSULATION	Buildings are not adequately insulated Need for renovation	Improve efficiency Adapt to local climate conditions – climate change
LACK OF FLEXIBILITY	Limited opportunities for reuse materials Demolition	Modularity and prefab Design for disassembling Customisation
TRANSPORT EMISSIONS	Materials extraction and transport Value chain	Local materials and production Reduced number of suppliers
DESIGN	Difficult to make changes during the process Control of materials	Design optimisation Digitalisation – BIM Functionally graded materials

Main barriers for AM adoption in construction have been identified in:

CAPACITY	Inadequate AM capacity: Lack of providers and skills. Existing AM capacity remains inadequate, with the majority of projects requiring manual finishing. Limited choice of materials: AM practice is currently focused on concrete building shells. Limitations are seen in the range of materials compatible with 3D printing, comprehensive building material databases and innovation in materials development. The incorporation of waste-based materials is limited and there are concerns about the mechanical properties and performance of bio-materials.
KNOWLEDGE	Skill shortage - Lack of trained professionals to operate 3D printers Aesthetic concerns - concerns from clients and architects about the appearance Lack of knowledge sharing
TECH STACK	Software and tools - Printing technology and software are well developed from other industries No practised design for AM - Lack of methodologies and tool support Disconnection between technicians and designers Industry reluctance to embrace new technologies and lack of systems engineering
LOGISTICS	Traditional and complex value chain Providers and suppliers - lack of innovation Logistic for AM on-site or off-site
REGULATIONS	Lack of additive manufacturing (AM) regulations and safety standards Regulations, standards: often used in combination with concrete or timber structures, or approved using brick regulations Lack of experimental data Lack of standardised approaches and documentation for the long-term performance of 3D printing technology
INVESTMENTS	Concerns about durability Lack of "first movers" High initial investment, maintenance costs, and low profit margins for construction companies, often reluctant to invest in innovation

3. IDENTIFIED AREAS OF INTEREST

The comprehensive analysis highlights two primary areas where Additive Manufacturing (AM) can significantly impact the construction industry: Sustainability and Flexibility. By addressing these areas, AM has the potential to align construction practices with global climate goals while enabling innovative, adaptive designs.

Sustainability (GHG Emissions)

- Reduction in waste and resource consumption through precise material usage.
- Adoption of sustainable and biogenic materials, such as wood, hemp, and algae-based inputs.
- Creation of resource-efficient structures and systems that optimize design while minimizing emissions.
- Integration of Life Cycle Assessment (LCA) during the design phase to evaluate and mitigate environmental impacts.
- Promotion of local materials and production to reduce transport-related emissions.

By focusing on these two fields, a strategic framework can be developed to drive the wider adoption of AM technology. Four main areas can be identified to describe the use and development of AM in construction.

Flexibility

- Support for modular construction, enabling reuse and adaptability of building components.
- Design for disassembly to enhance circularity and reduce waste at the end of a building's lifecycle.
- Customization and design optimization for specific applications, including retrofitting.
- Seamless on-site versus off-site production methods for better logistics and efficiency.

FOCUS AREA	DESCRIPTION	KEY BENEFITS
1 **LOW EMISSIONS MATERIALS – LOW FLEXIBILITY**	Building large structures using recycled or innovative materials; emphasis on material efficiency.	Waste reduction, resource minimization, on-site production options.
2 **HIGH EMISSIONS MATERIALS – LOW FLEXIBILITY**	Use of conventional materials for large structures, with reduced emissions compared to traditional methods.	Increased productivity, on-site CO_2 reductions, elimination of formwork.
3 **LOW EMISSIONS MATERIALS – HIGH FLEXIBILITY**	Modular and component-level systems using biogenic or recycled materials for adaptability and circularity.	GHG reduction, circularity, high design flexibility, biomaterial adoption.
4 **HIGH EMISSIONS MATERIALS – HIGH FLEXIBILITY**	Systems-level design for components using conventional materials, focusing on modularity and adaptability.	Enhanced efficiency, lightweight materials, reduced CO_2 emissions.

1 LOW EMISSIONS MATERIALS – LOW FLEXIBILITY

Focus Area 1 addresses the theme of building large structures using recycled or innovative materials, applying technologies capable of 3D printing entire buildings on-site. Currently, the level of adoption is low and limited to research projects and prototypes.

There are several barriers to widespread adoption, including the uncertainty of durability based solely on simulations, transport emissions associated with off-site production, and the need for specialised labour. In addition, there is a lack of a comprehensive building materials database, a limited range of materials and insufficient experimental data.

The main gatekeepers in this area can be identified with contractors, who require proven solutions and long-term performance, and legislators, due to a lack of standards and building codes. However, the adoption of Additive Manufacturing could offer significant benefits, such as the use of recycled materials, waste reduction, minimised resource consumption, on-site/off-site production flexibility and increased safety.

To overcome the barriers, potential strategies include integrating life cycle considerations into the design phase, incorporating MEP (Mechanical, Electrical, Plumbing) aspects, analysing material performance, establishing partnerships with local material suppliers, promoting disassembly opportunities, encouraging automation/BIM integration and developing standardised components.

2 HIGH EMISSIONS MATERIALS – LOW FLEXIBILITY

Focus Area 2 focuses on building at the scale of large structures using conventional materials, leveraging 3D printing technology to reduce emissions compared to traditional construction methods. Currently, the level of adoption is high, and 3D printed buildings are becoming a reality worldwide. The largest development of the 3D printing technology is seen in this area.
Despite this success, there are several barriers to further widespread adoption. These include the high cost and transportation challenges associated with printers, durability concerns, low integration of other components, lack of knowledge sharing, building codes, aesthetic concerns, and building size limitations due to material constraints.

The key gatekeepers in this area are contractors, because of questions about durability, sustainability and mechanical properties, and clients and architects, who are concerned about aesthetics and often reluctant to share knowledge.

The benefits of additive manufacturing (AM) in this context include on-site production with reduced CO_2 emissions, increased productivity compared to traditional concrete structures, elimination of formwork, and improved site safety. To overcome existing barriers, potential strategies include advocating for the development of a regulatory framework, implementing the use of local materials, new materials and additives, integrating life-cycle considerations into the design phase, incorporating building components through Building Information Modelling (BIM), and adopting a standardised approach to 3D printing in construction.

3 LOW EMISSIONS MATERIALS – HIGH FLEXIBILITY

Focus Area 3 is focused on working at the component level with a systems thinking approach, emphasising recycled, biogenic or innovative materials and off-site production. This approach allows for tailor-made elements to be designed to meet the specific needs of a construction project, offering greater compliance compared to the construction of entire buildings. Incorporating bio or recycled materials not only facilitates compliance, but also results in significant reductions in GHG emissions and provides greater design flexibility.

Currently, the level of adoption is low, mainly limited to research projects and prototypes, with a focus on interior design. Barriers to widespread adoption include concerns about the durability of bio- and living materials, lack of education and skills among designers and manufacturers, lack of standards for bio- and innovative materials, difficulties in testing materials and components for different performances (thermal, structural, fire, etc.), and uncertainties in identifying possible applications and redesigns for printing.

Key gatekeepers in this area include contractors, due to lack of knowledge and scepticism about new materials, and manufacturers, due to challenges related to printing and using new materials. The benefits of additive manufacturing (AM) in this context include sustainability with reduction of greenhouse gas emissions, circularity, the ability to work with biomaterials and living materials for new geometries, increased design complexity coupled with resource efficiency, and the incorporation of design for disassembly and modularity.

To overcome the identified barriers, potential strategies include a focus on the component level, the development of customised components in situ (retrofitting), design and material optimisation, the integration of LCA and BIM in the design phase, and the establishment of partnerships with material suppliers.

4 HIGH EMISSIONS MATERIALS – HIGH FLEXIBILITY

Focus Area 4 addresses systems thinking at the component level with a focus on conventional materials. This approach involves designing components for defined areas of buildings, promoting design for disassembly and modularity, while using traditional building materials. Despite its potential, adoption is currently low and mainly limited to research projects and prototypes.

There are several barriers to widespread adoption, including a lack of knowledge about structural properties, the need for further testing, sustainability concerns and existing building regulations. Key gatekeepers in this area include end-users and clients, due to a lack of knowledge on the opportunities offered by AM, and contractors, due to a lack of tested solutions, long-term performance and safety considerations.

The benefits of AM in this context include the incorporation of functionally graded materials, the use of lightweight aggregates, parameterisation and seamless integration into the design process.

To overcome the identified barriers, potential strategies include increasing modularity, demonstrating increased efficiency and reduced CO_2 emissions, seamless integration of these structures into buildings, incorporating LCA at the design stage, and advocating for the development of a regulatory framework. These strategies aim to pave the way for wider adoption of AM at the component level with a systems thinking approach using conventional materials.

One of the key objectives of this analysis is to identify potential applications of Additive Manufacturing in construction and to test them in practice.

4. CONCLUSIONS AND RECOMMENDATIONS

The findings of this report underline the critical role of Additive Manufacturing (AM) in addressing the environmental and efficiency challenges of the construction sector.

Focus Area 3: Low Emission Materials - High Flexibility emerges as the most strategic area for exploration and development, given its alignment with the SDGs and the need for adaptive construction solutions.

Key conclusions:

1 Innovation at component level: AM offers scalable opportunities to develop modular, low-emission components that are resource efficient and readily compliant with building regulations.

2 Synergy with bio-based materials: The use of biogenic materials alongside AM technology reduces GHG emissions while enabling innovative and functional designs.

3 Circularity and adaptability: Emphasising design for disassembly and modularity is critical to minimising waste and extending the life cycle of materials and components.

In order to promote the integration of AM and bio-based materials in architecture and construction, the following strategic actions are proposed.

Recommendations and Future Actions

1. **STRATEGIC PARTNERSHIPS:** Collaboration is essential to accelerate innovation and overcome existing barriers. Partnerships between bio-based material producers, AM technology providers and research institutions can drive the co-development of innovative components. By addressing challenges related to scalability, durability and testing, these collaborations will ensure that bio-based and recycled materials achieve commercial viability.

2. **MATERIAL AND DESIGN INNOVATION:** Emphasis should be placed on the development of multi-functional components that combine structural, insulating and aesthetic properties. Materials and processes must prioritise circularity, incorporating strategies such as design for disassembly and reuse. This approach is in line with the principles of the circular economy, while promoting performance-oriented material solutions.

3. **LIFECYCLE INTEGRATION AND STANDARDS:** Integrating Life Cycle Assessment (LCA) into early design workflows will enable the assessment of emissions, durability and recyclability, ensuring that AM processes meet sustainability goals. In addition, advocacy for regulatory frameworks and standardised testing protocols is critical to facilitate wider adoption of AM technologies in the construction industry.

4. **PILOT AND DEMONSTRATION PROJECTS:** Pilot projects are an important mechanism for demonstrating the potential of AM, particularly in retrofitting and modular construction. By using bio-based materials, these projects can generate valuable data, refine fabrication methods and demonstrate feasibility to key stakeholders, thereby fostering wider industry confidence in AM solutions.

5. **KNOWLEDGE SHARING AND CAPACITY BUILDING:** Knowledge sharing initiatives are needed to address knowledge gaps and skills shortages. Workshops, open access databases and training programmes on AM technologies and biomaterials can enhance capacity building and ensure that both emerging and established professionals are prepared to integrate these innovations effectively.

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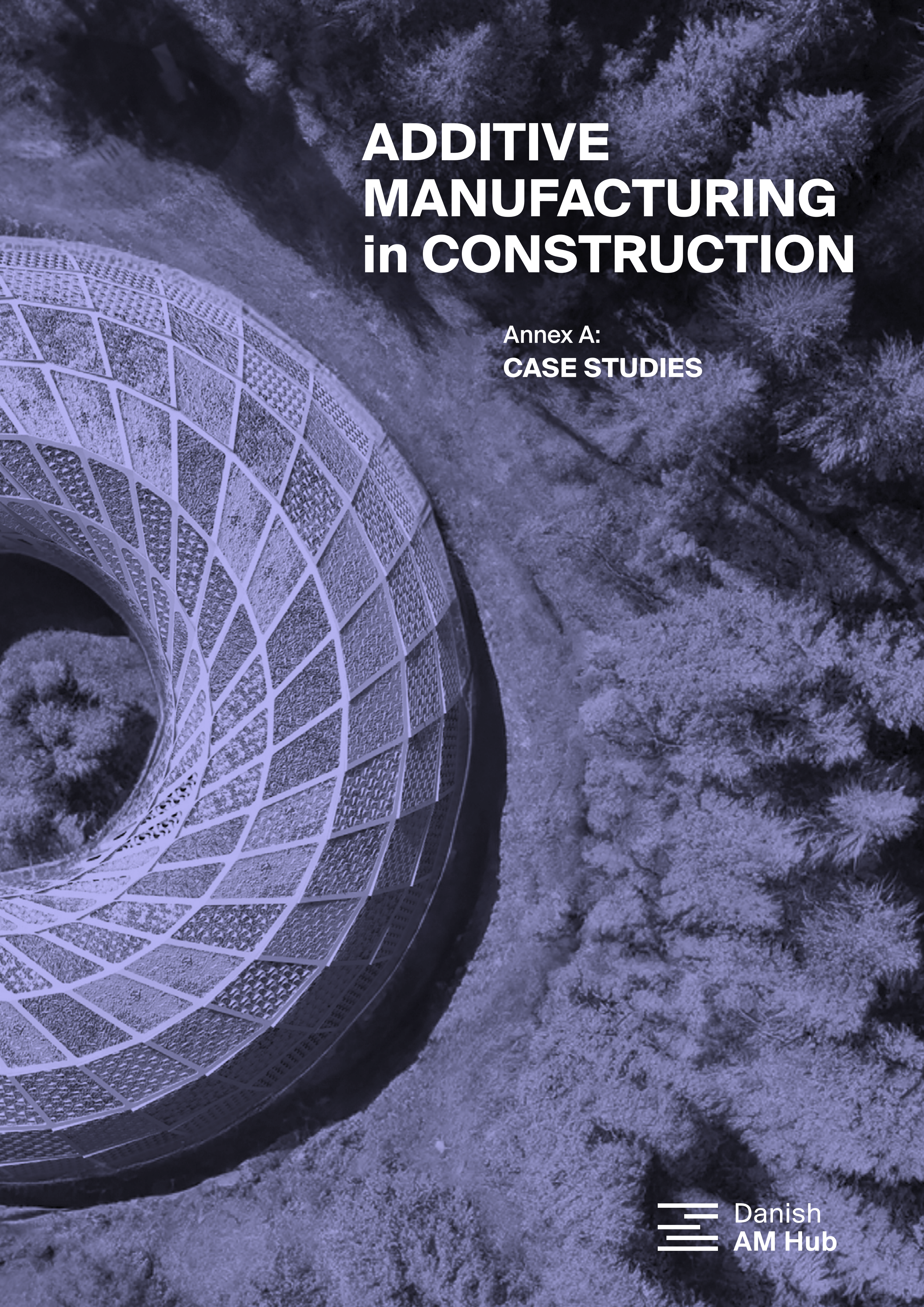
Danish
AM Hub



ADDITIVE MANUFACTURING in CONSTRUCTION

Annex A:

CASE STUDIES

Danish
AM Hub

The case studies in this annex have been carefully selected to reflect the evolving role of additive manufacturing (AM) in the construction industry.

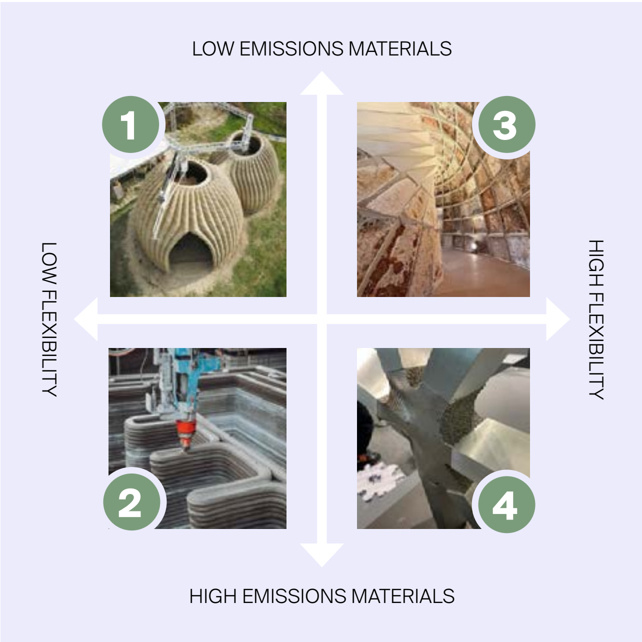
Selected to reflect a wide range of materials, design approaches, and applications, these projects highlight the potential of AM to address key challenges in the built environment. From sustainable material use and resource efficiency to digital fabrication and novel architectural expression, each case study provides valuable insights into the role of AM in advancing innovation and sustainability. By presenting examples that span experimental research, industrial applications, and emerging best practices, this collection underscores the growing impact of AM across scales and typologies.

The selection follows the framework presented in the report, which categorises AM applications according to their material emissions and flexibility. This graph positions the case studies in four quadrants, based on the emissions associated with their materials and the adaptability of their designs.

In this context, 'low flexibility' refers to building-level applications where the AM printed structure is fixed and cannot be modified once completed. These cases typically focus on large-scale construction, demonstrating how AM can improve sustainability within long-lasting structures. In contrast, 'high flexibility' is related to projects at the component level, where AM is used to create modular elements that can be assembled, disassembled, or adapted over the life of the building.

The distinction between "high-emission" and "low-emission" materials relates to the type of materials used. High-emission materials are typically conventional in the construction industry, such as concrete or steel.
In contrast, low-emission materials include bio-genic, recycled, or circular materials that can reduce environmental impact.

The case studies presented in this annex fall into these categories, providing a comprehensive view of how AM technologies can drive both environmental and design innovation in construction.



www.am-hub.dk/construction

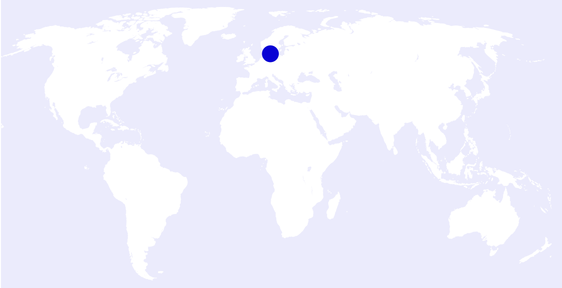
I AM MSHRM

Closing waste loops through additive manufacturing

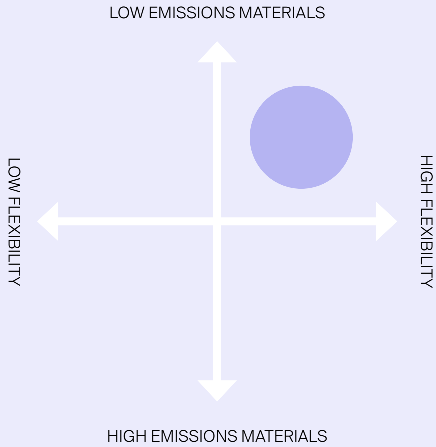
I AM MSHRM, a project developed by Danish AM Hub and Bjarke Ingels Group (BIG), is an example of how the combination of 3D printing and bio-based materials can promote environmental sustainability.

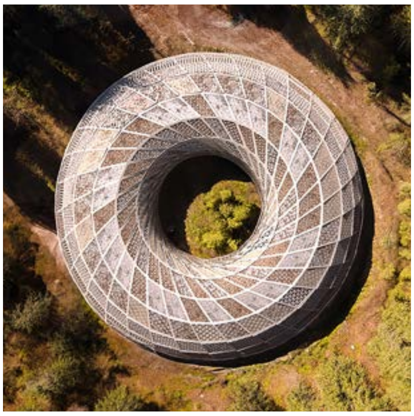
The modular pavilion combines 3D printed recycled plastic and baked mycelium. It is designed to be dismantled, reassembled or recycled after use, responding to urban and construction waste challenges. The technology allows the creation of complex curved structures that would be inefficient to produce using traditional methods.

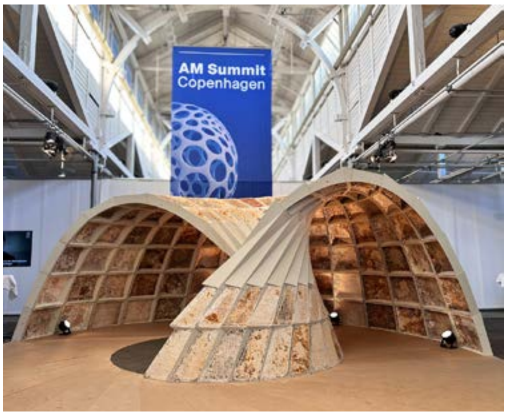
According to the Danish AM Hub's CO_2e calculator, the pavilion emits less than 20% of the CO_2 of a comparable structure built with conventional materials. The I AM MSHRM system has the potential to be scaled up for different applications, such as temporary housing or community spaces, using locally sourced waste materials.



Year:	2023-2024
Location:	Copenhagen, Denmark
Project:	Danish AM Hub & BIG
Typology:	Pavilion
Themes:	Circularity, bio-materials, local materials, system
Sources:	Danish AM Hub, BIG
Case study ID:	001







IMAGES BY BJARKE INGELS GROUP (BIG)

reMARBL3D

at TIME SPACE EXISTENCE, Venice, 2023

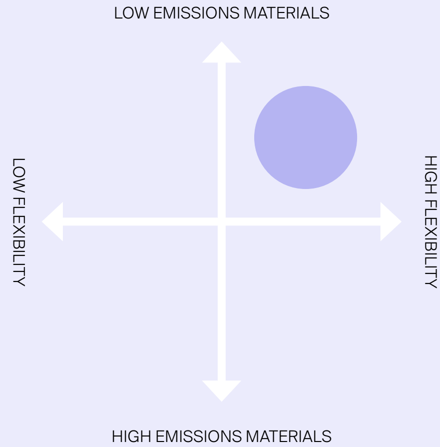
Researchers at ETH Zurich and SUPSI's Institute of Earth Sciences have developed a dry-assembled funicular floor composed of 17 blocks 3D printed with recycled marble aggregates - approximately 80% of the printed material.

This 3D printing process enables the manufacture of large-scale components suitable for structural applications using byproducts of stone extraction.

The disposal of construction and quarry waste poses a significant environmental challenge, with up to 40% of this waste ending up in landfill. By transforming this waste into valuable construction products, the research addresses both waste management and the need for new materials.

The 3D printing method used is Binder Jetting (BJT), which uses a two-component binder system. A granular base is combined with an activating liquid alkali solution, which is sprayed through nozzles in layers, resulting in durable printed parts with excellent mechanical properties and resistance to weather and fire.

Year:	2023
Location:	Venice Architecture Biennale, Italy
Project:	ETH, Digital Building Technologies
Typology:	Structures
Themes:	Circularity
Sources:	ETH Zurich / NCCR Digital Fabrication
Case study ID:	002



REMARBL3D AT VENICE ARCHITECTURE BIENNALE 2023

ETH zürich dbt Digital Building Technologies

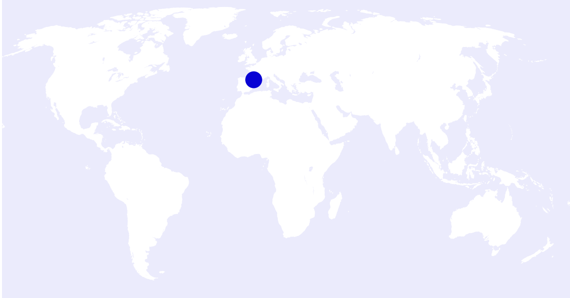
TOVA

3d-printed Earth Architecture

The Institute for Advanced Architecture of Catalonia (IAAC) has developed TOVA, Spain's first 3D printed earth building, located at the IAAC's Valldaura Labs near Barcelona. Built in seven weeks using the Crane WASP 3D printer, TOVA uses 100% local materials sourced within a 50-metre radius, resulting in zero waste and minimal carbon emissions.

The walls of the structure are made of local soil mixed with additives and enzymes to improve structural integrity and elasticity for optimised 3D printing. The foundation is made of geopolymer and the roof is made of wood.

TOVA serves as a prototype bridging traditional earthen architecture and modern 3D printing technology, offering a potential solution to current climate and housing challenges.



Year:	2022
Location:	Barcelona, Spain
Project:	IAAC
Typology:	Housing
Themes:	Bio-materials
Sources:	IAAC
Case study ID:	003

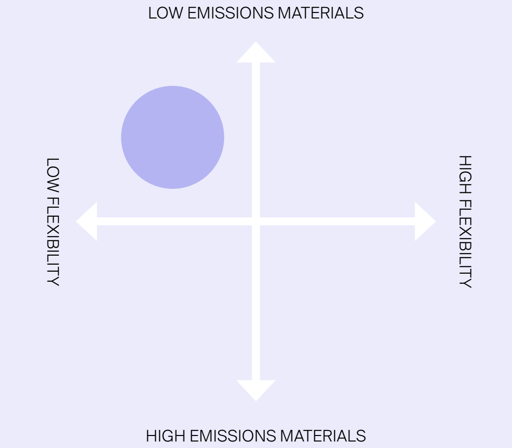


IMAGE BY GREGORI CIVERA

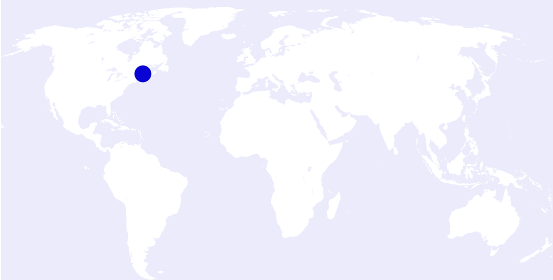
Iaac Institute for advanced architecture of Catalonia

HIVE PROJECT

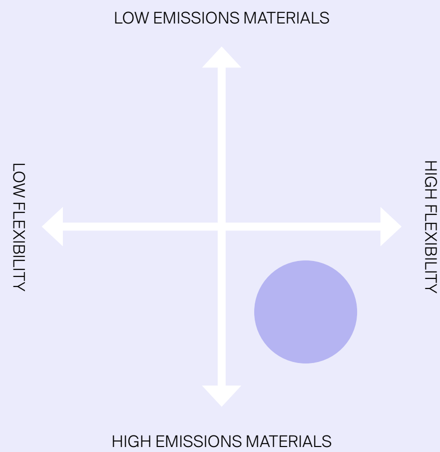
Traditional Craftsmanship and Digital Innovation

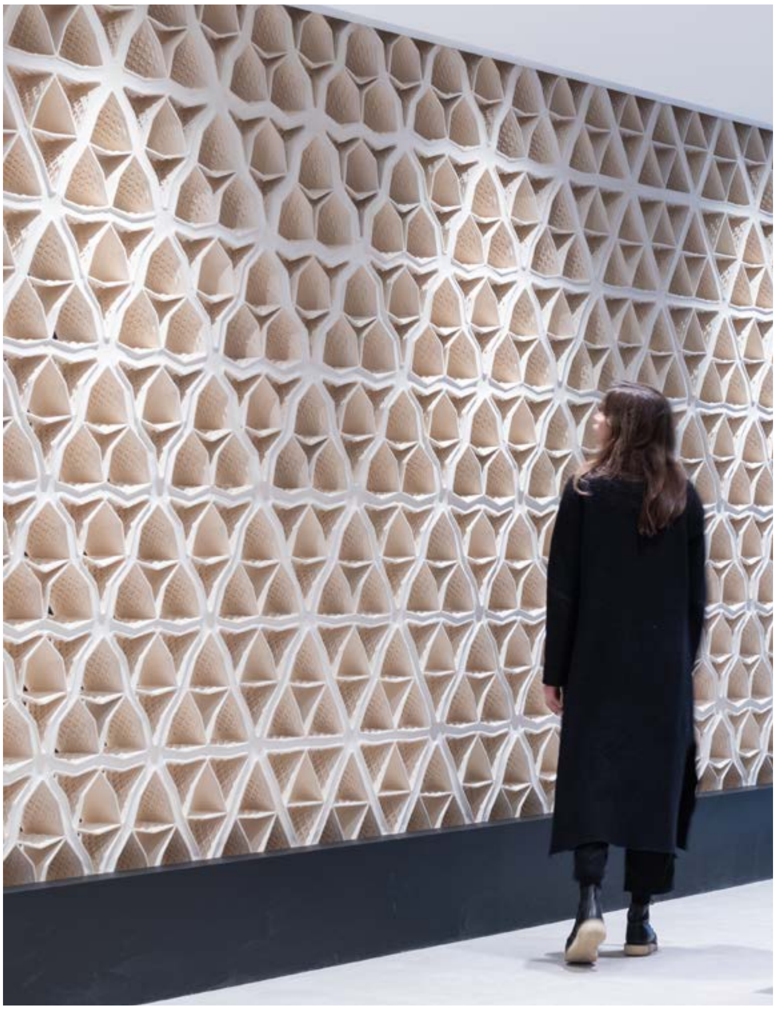
The HIVE project is a 3D-printed masonry wall built by a team from the University of Waterloo in Toronto, Canada. Designed by SDI Interior Design for Investment Management Corporation of Ontario, the wall is made of 175 unique 3D-printed clay bricks, each designed with different openings to balance privacy and light transmission. The hexagonal aggregation of these units creates a structurally efficient form reminiscent of a honeycomb.

The development process involved extensive testing of materials, designs and manufacturing techniques. The team combined traditional ceramic materials with advanced geometric design and robotic precision to achieve the final structure. This approach blends the principles of traditional ceramic craftsmanship with modern technology, allowing for new forms of material expression and geometric complexity in masonry construction.



Year:	2021
Location:	Toronto, Canada
Project:	University of Waterloo
Typology:	Building components
Themes:	System, conventional materials
Sources:	SDI Interior Design, University of Waterloo
Case study ID:	004





IMAGES BY SHABAAN KHOKHAR

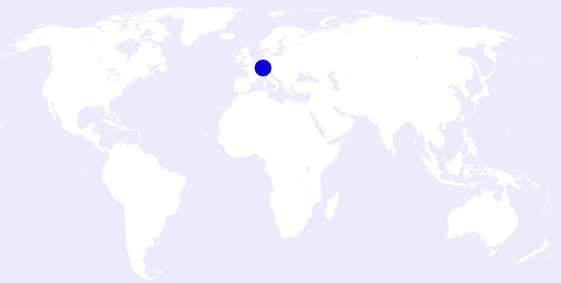
HEXASTONE

Design for disassembly

The Hexastone Pavilion, a collaboration between Technische Hochschule Lübeck, Vertico, and Sika, is a 4.5-meter diameter dome composed of 102 unique interlocking stones. Each stone was 3D-printed over two days, utilizing a fully digitized process that allows for a vast range of geometries.

The pavilion's design employs a computational form-finding process to create a compression-only shell structure. Designed with sustainability in mind, the pavilion embraces a "Design for Disassembly" approach.

The shell is tessellated into planar hexagonal tiles, facilitating efficient printing on a flat bed and simplifying the connections between individual stones. Unlike traditional brickwork that uses tapered mortar joints to achieve curvature, Hexastone generates curvature through the individually inclined perimeters of each hexagonal stone, resulting in parallel crevices between them. Contact surfaces are coated with a non-adhesive agent to prevent tensile force transfer and facilitate easier disassembly, promoting a sustainable construction methodology.



Year:	2023
Location:	Neumünster, Germany
Project:	Technische Hochschule Lübeck, Vertico, Sika
Typology:	Pavilion
Themes:	Conventional materials, system
Sources:	Parametric Architecture
Case study ID:	005

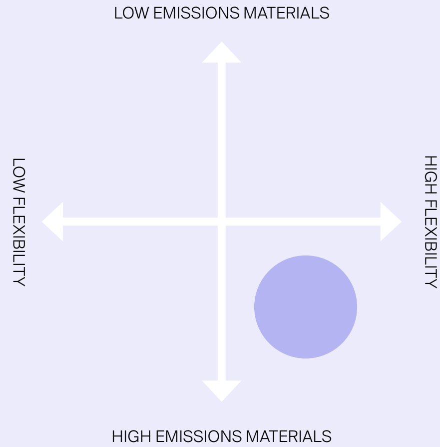


IMAGE COURTESY OF TECHNISCHE HOCHSCHULE LÜBECK

TECHNISCHE HOCHSCHULE LÜBECK

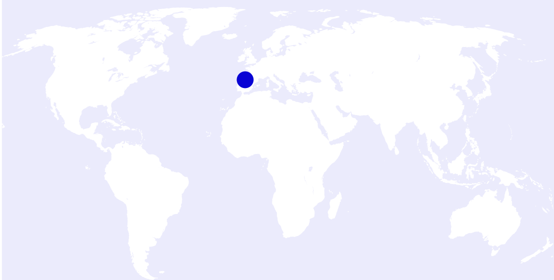
ECOALF STORE

Plastic Waste into Sustainable Design

A net-zero, zero-waste boutique in Madrid is the result of a collaboration between Ecoalf and Nagami. The interior features walls, shelves and display tables entirely made from 3.3 tonnes of 100% recycled plastic. The components were 3D printed to resemble melting glaciers to raise awareness of climate change.

The use of recycled plastic in the store's construction not only diverts waste from landfill, but also showcases the potential of 3D printing technology in sustainable design. By sourcing materials locally in Spain and manufacturing components locally, the project minimises the carbon emissions associated with transportation and manufacturing.

This approach provides a model for reducing the environmental impact of retail design, highlighting the feasibility of integrating recycled materials into commercial spaces.



Year:	2023
Location:	Madrid, Spain
Project:	Nagami
Typology:	Interior design
Themes:	System, circularity, local materials
Sources:	Nagami, ArchDaily
Case study ID:	006

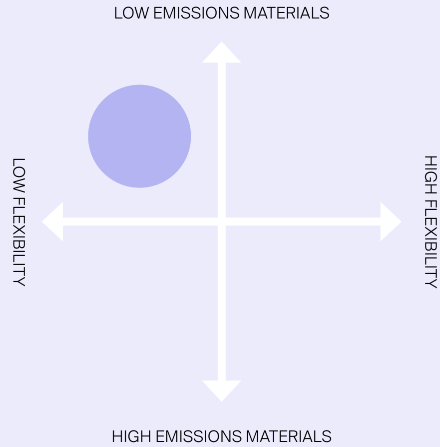


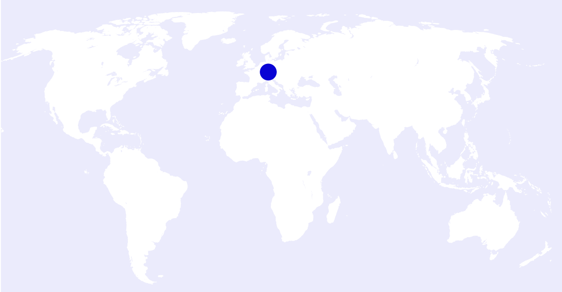

IMAGE BY ALFONSO QUIROGA

RADICANT

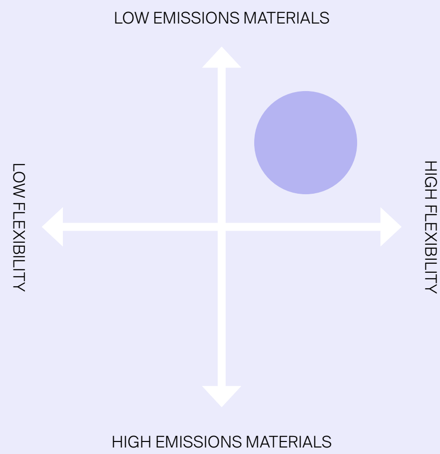
Pioneering Sustainable Biopolymer Architecture

The project, developed by the Centre for Information Technology and Architecture (CITA) at the Royal Danish Academy, explores the use of biopolymer composites derived from agricultural waste streams to create a 3D printed wall paneling system. The composite material consists of bone glue, a by-product of the meat industry, combined with cellulose fibres from various waste streams. The mixture is robotically 3D printed into filigree leaf-like patterns.

Due to the thermoplastic properties of bone glue, the material can be reactivated and reshaped by localised heating, facilitating processes such as repair, refurbishment and recycling. Such adaptability supports the principles of circular design by allowing the material to be reused and reconfigured, thereby extending its life cycle and reducing waste. Radicant was part of the Living Prototypes exhibition at Aedes Architecture Forum in Berlin from 10.12.2022 - 25.01.2023.



Year:	2022-2023
Location:	Berlin, Germany
Project:	Royal Danish Academy, CITA, DTU
Typology:	Interior design
Themes:	Bio-materials, circularity
Sources:	Royal Danish Academy
Case study ID:	007



Nicholas, P., Lharchi, A., Tamke, M., Eppinger, C., Sonne, K., Rossi, G., & Thomsen, M. (2023). Biopolymer Composites in Circular Design: Malleable materials for an instable architecture. Conference: Acadia 2023: HABITS OF THE ANTHROPOCENE: SCARCITY AND ABUNDANCE IN A POST-MATERIAL ECONOMY. PROCEEDINGS OF THE 43RD ANNUAL CONFERENCE OF THE ASSOCIATION FOR COMPUTER AIDED DESIGN IN ARCHITECTURE. University of Colorado, Denver.

3D PRINTED FILM STUDIO

3D printing and lighting fusion

In 2023, designer Philipp Aduatz, in collaboration with set designer Dominik Freynschlag and 3D concrete printing manufacturer incremental3d, developed the world's first 3D-printed film studio for the Casinos Austria and Austrian Lotteries Group.

The studio features a concrete wall constructed from 60 individual segments, each produced using a special white cement-based mortar. These segments are assembled into a structure measuring 630 cm in width, 330 cm in depth, and 230 cm in height, with a total weight of 3,500 kg.

The wall incorporates 14 horizontally inserted LED strips, each matching the thickness of the 3D-printed layers. All LED elements are integrated into the studio's lighting system via computer-aided control, enabling an almost unlimited number of color combinations. By combining 3D printing with smart LED technology, the project demonstrates a novel approach to studio design, offering new possibilities for creating unique atmospheres and enhancing the versatility of film production environments.

Year:	2023
Location:	Vienna, Austria
Project:	Casinos Austria & Austrian Lotteries Group
Typology:	Interior design
Themes:	Conventional material, MEP Integration
Sources:	Philipp Audatz
Case study ID:	008

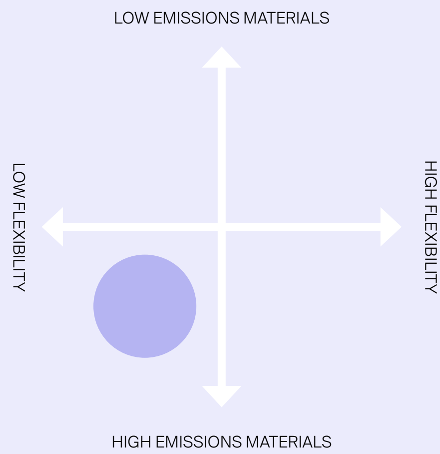


IMAGE COURTESY OF PHILIPP ADUATZ

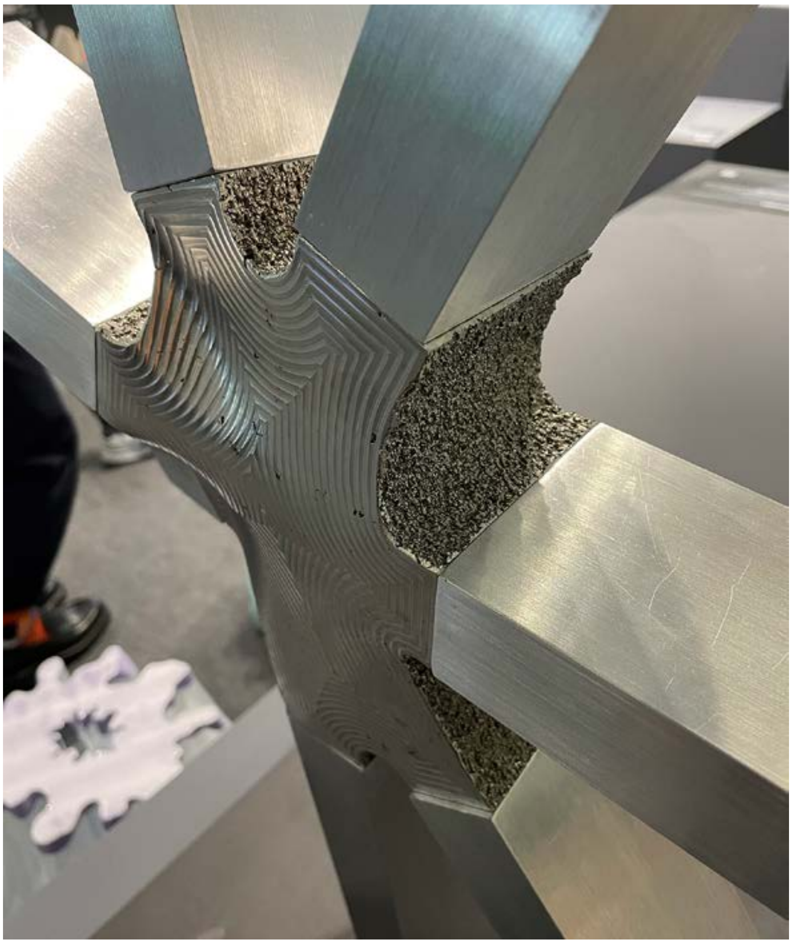
InNoFa-DEMONSTRATOR

Individual node facades

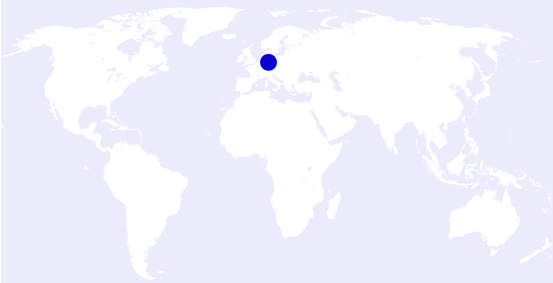
The FLEX research group at the University of Applied Sciences Leipzig (HTWK) and the Laserinstitut Hochschule Mittweida (LHM) have developed the InNoFa2.0. The single-node façade component is manufactured using a new large-volume powder bed-based 3D printing technology that combines technologies from different additive manufacturing processes.

These features greatly increase the material turnover during the process, reduce the printing time and lower the material costs.

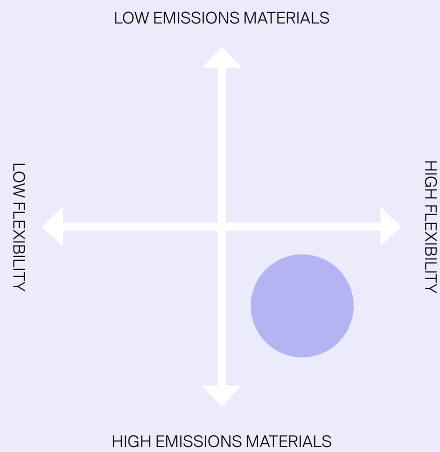
This technique holds great potential for larger components. The InNoFa2.0 demonstrator is based on the ParaKnot3D concept, a hybrid construction that combines straight rods and individual knot elements to create optimised free-form structures.



INNOFA2.0 DEMONSTRATOR AT FORMNEXT 2023



Year:	2023
Location:	Leipzig, Germany
Project:	FLEX, HTWK Leipzig, LHM
Typology:	Building components, structures
Themes:	System, conventional materials
Sources:	[HTWK-Liepzig]
Case study ID:	009



HTWK
Hochschule für Technik, Wirtschaft und Kultur Leipzig

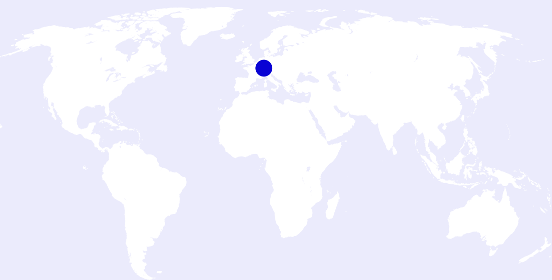
FLEX
FORSCHUNG.LEHRE.EXPERIMENT

THE WAVE HOUSE

Europe’s largest 3D printed building

Europe’s largest 3D printed building, the Wave House Data Centre, was inaugurated in Heidelberg, Germany, marking a major milestone in innovative construction. The project, developed by PERI 3D Construction and HeidelbergCement, used COBOD’s BOD2 3D construction printer to build the structure.

A key design challenge was overcome by architects SSV and Mense Korte, who incorporated a unique wave design into the walls. Such intricate wave-shaped walls would not have been possible using conventional construction methods, so 3D printing was chosen for its design flexibility. The building demonstrates the potential of 3D printing to create complex, energy-efficient structures and provides a scalable solution for future data centre developments.



Year:	2024
Location:	Heidelberg, Germany
Project:	SSV Architekten, Mense-Korte
Typology:	Structures
Themes:	Conventional materials
Sources:	[COBOD International]
Case study ID:	010

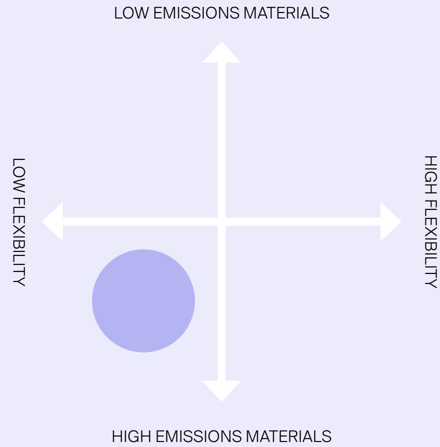


IMAGE COURTESY OF COBOD

STRESS-BASED DESIGN

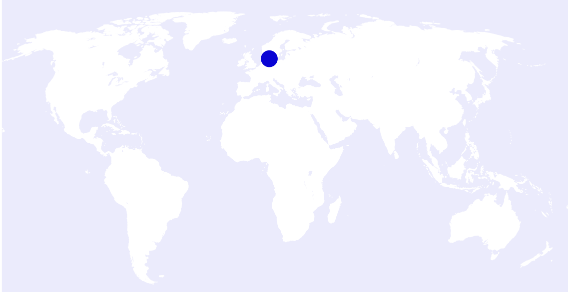
For 3D concrete printed horizontal structures

DLightBeam+ is the second iteration of the 3DLightBeam research project, which aims at combining computational design with the freedom of shape provided by the 3D Concrete Printing (3DCP) technology to challenge conventional reinforced concrete structures by exploring new design solutions for carbon-efficient concrete beams.

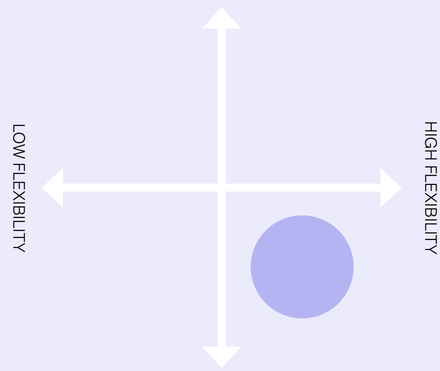
3DLightBeam+ enables structurally reliable load-bearing printed beams with carbon reduction through multi-hierarchical stress-based design optimization.

3DLightBeam+ is shape-optimised to maximise bending capacity while reducing weight. Its internal infill design is inspired by the layout of the structure of bones, to work in pure compression and tension. A high-resolution material deposition is achieved by data-driven robot control, allowing us to deploy concrete and steel reinforcements only where needed, avoiding material inefficiencies.

The structure can be applied in existing construction sites and, at this stage, reduce concrete CO_2 emissions by 19.3%.



Year:	2023
Location:	Odense, Denmark
Project:	Create, SDU
Typology:	Structures
Themes:	Conventional materials
Sources:	SDU Create
Case study ID:	011



BRESEGHELLO, L. (2023). STRESS-BASED DESIGN OF LIGHTWEIGHT HORIZONTAL STRUCTURES FOR 3D CONCRETE PRINTING. [PH.D. THESIS, CREATE SDU]. SYDDANSK UNIVERSITET. DET TEKNISKE FAKULTET. HTTPS://DOI.ORG/10.21996/JMYD-S840
BRESEGHELLO, L., HAJIKARIMIAN, H., JØRGENSEN, H. B., & NABONI, R. (2023). 3DLIGHTBEAM+. DESIGN, SIMULATION, AND TESTING OF CARBON-EFFICIENT REINFORCED 3D CONCRETE PRINTED BEAMS. ENGINEERING STRUCTURES, 292, 116511. HTTPS://DOI.ORG/10.1016/J.ENGSTRUCT.2023.116511

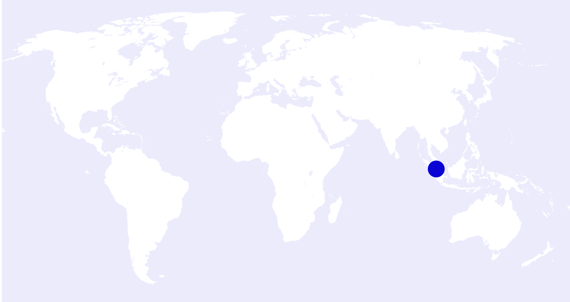
TIFFANY FAÇADE

Coral-inspired 3D-printed façade

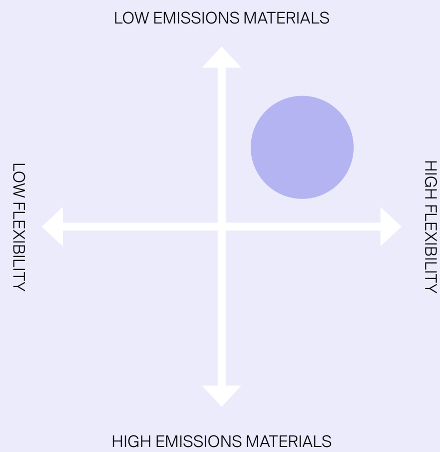
The Tiffany & Co. store façade designed by MVRDV features a coral-inspired screen, 3D printed using recycled plastic thanks to the assistance of Amsterdam-based company Aectual and Milan-based engineers BUROMILAN.

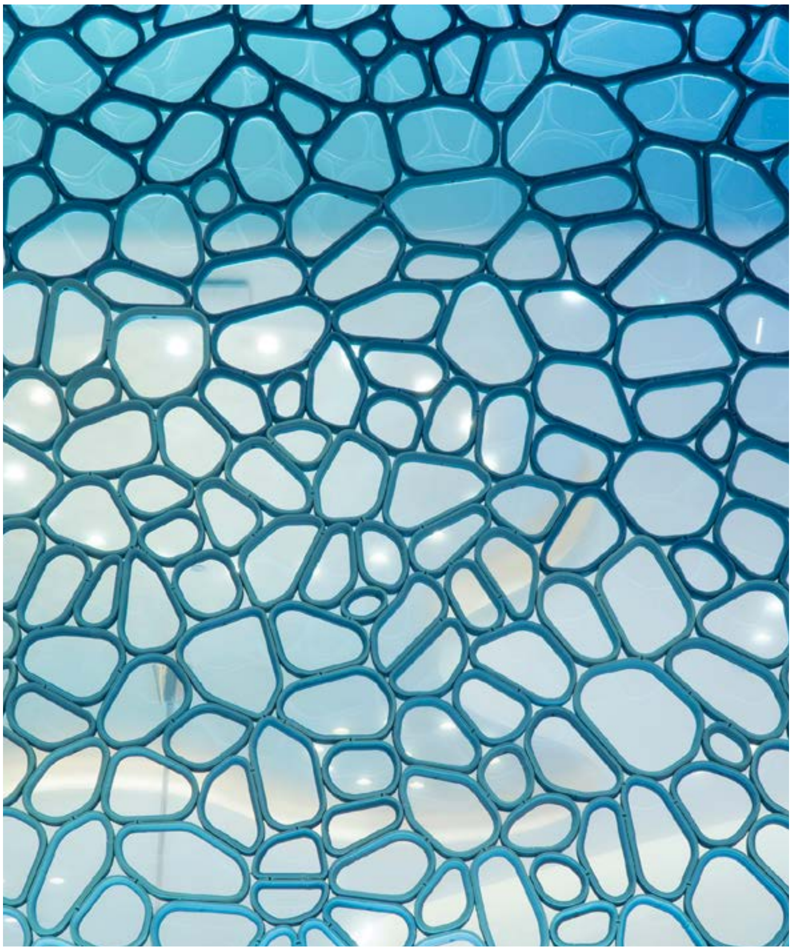
Using the patterns seen in Singapore's coral reefs as a guide, the team designed a screen to cover the store's façade with an organic, cell-like pattern. 3D printing experts developed a process to produce the 50-millimetre-thick screen using recycled plastic, including reclaimed and recycled fishing nets.

By making use of this unusual source of recycled plastic, the design not only draws inspiration from the oceans, but also plays a part in protecting them. A particularly challenging task was to meet the stringent regulations for fire safety required in an airport, solved by adding a chemical to the mixture that is also manufactured using seawater.



Year:	2023
Location:	Singapore Changi Airport
Project:	MVRDV, Aectual, BUROMILAN
Typology:	Building components
Themes:	Circularity, system
Sources:	[MVRDV]
Case study ID:	012





IMAGES BY MVRDV

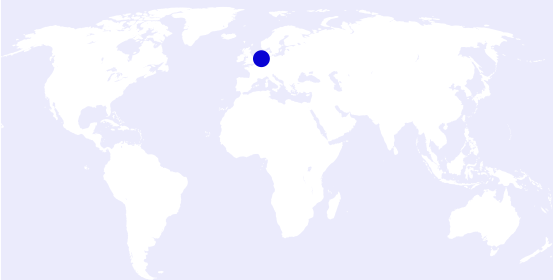
CERAMIC HOUSE

A facade inspired by knitwear

Through a creative interplay of 3D printed ceramic tiles and imaginative design, Studio RAP fused tradition and modernity, drawing inspiration from knitwear and the city's rich ceramic heritage.

The building's facade is made up of 225 unique tiles - 3D printed ceramic tiles that mimic the appearance of rippling textiles. Fired at high temperatures to ensure durability and weather resistance, the tiles were produced using a clay 3D printing process, with each tile taking approximately two hours to print.

The wavy, textile-like texture of the tiles was achieved by precisely controlling the layering during the printing process, creating a three-dimensional effect that enhances the visual depth of the façade and integrates seamlessly with traditional construction methods.



Year:	2023
Location:	Amsterdam, The Netherlands
Project:	Studio Rap
Typology:	Building components
Themes:	Conventional materials
Sources:	Studio RAP
Case study ID:	013

LOW EMISSIONS MATERIALS

LOW FLEXIBILITY

HIGH FLEXIBILITY

HIGH EMISSIONS MATERIALS

IMAGE BY RICCARDO DE VECCHI

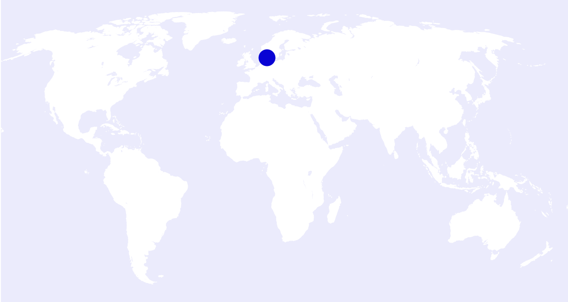
RAP

WOHN HOMES

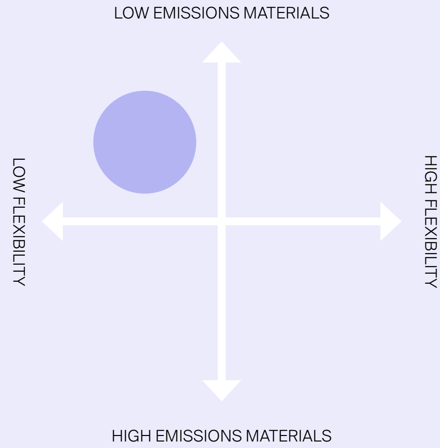
Redefining sustainable housing in 3D printing

WOHN A/S pioneers sustainable housing through advanced 3D printing, repurposing waste wood, glassfiber, and plastic for affordable, sustainable homes. Each 20m^2 home reuses 3 tons of waste, reducing CO_2 emissions by 90% compared to traditional construction methods.

The technology ensures high-quality, customizable designs without added costs, empowering homeowners to personalize spaces sustainably. These homes last over 60 years, designed for efficient recycling at their lifecycle's end, reflecting WOHN's commitment to sustainability.



Year:	2023
Location:	Sorø, Denmark
Project:	Wohn A/S
Typology:	Housing
Themes:	Circularity, system
Sources:	Wohn Homes
Case study ID:	014



IMAGES BY WOHN HOMES

WOHN HOMES AS A SERVICE

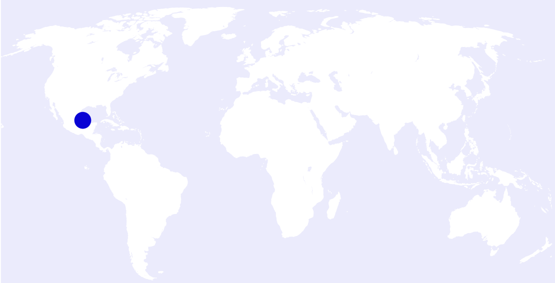
THE EGGSHELL PROJECT

Giving new life to biowaste

MANUFACTURA, a Mexican design studio, has launched 'The Eggshell Project' with the aim of transforming organic waste into sustainable building materials. With food waste accounting for a third of global production, this project seeks to address both environmental and socio-economic issues by reusing discarded eggshells. The project focuses on using these eggshells in combination with bio-binders to create bioceramic bricks, eliminating the need for traditional firing processes. The mixture is 3D printed into various geometric shapes, resulting in building components suitable for a variety of architectural applications.

The research led to the development of two primary structures: the Eggshell Wall, made up of 105 unique blocks that are assembled based on their geometry, and the Eggshell Column, made up of 26 interlocking pieces that provide stability through their shape. The eggshells used were collected over two months from various restaurants in Mexico City, ensuring a 100% sustainable and circular process.

By integrating computer-aided design with digital manufacturing, the project demonstrates the potential to transform organic waste into valuable building materials.



Year:	2023
Location:	Mexico City, Mexico
Project:	Manufactura
Typology:	Building components
Themes:	Circularity, bio-materials, local materials
Sources:	Designboom, 3Dprinting.com
Case study ID:	015

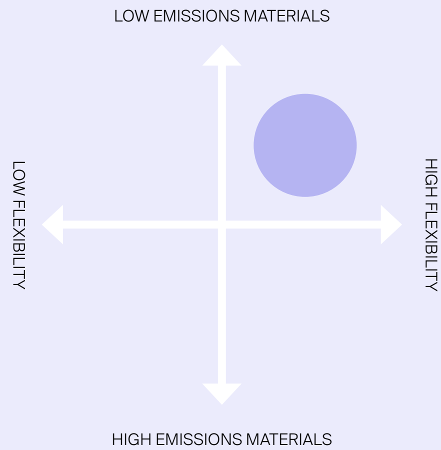


IMAGE BY ARTURO ARRIETA

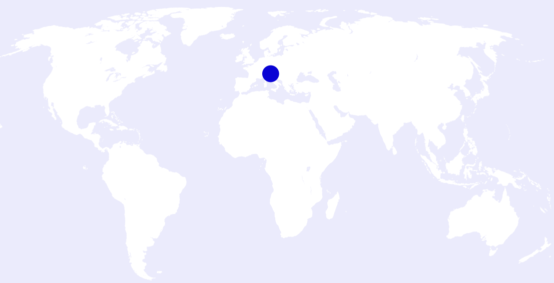
3DNATURDRUCK

Biocomposite Reciprocal Canopy

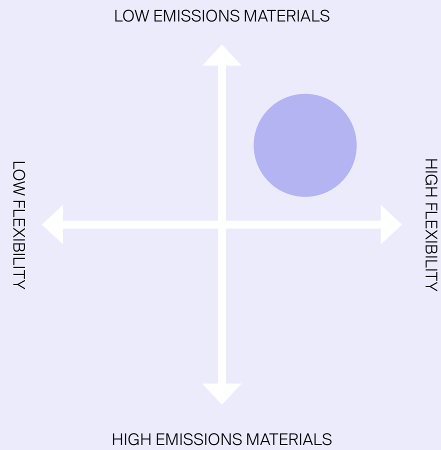
The project explores 3D printing in combination with annually renewable natural fibres, focusing on material development, structural analysis, fabrication methods and the application of this material-based technique to architectural design.

Specifically, the study investigates the use of 3D printed natural fibre reinforced filaments in different architectural contexts, tested through a series of demonstrators addressing different design challenges.

The structure was fabricated using a lightweight short fibre filament composed of wood fibres and bio-based PLA. As the material was developed specifically for this project, extensive testing was carried out to inform the digital simulations and to ensure the integrity of the structure. These tests have been instrumental in refining the printing process and validating the performance of the material for architectural applications. The project lays the groundwork for the integration of natural fibre-based 3D printing in construction.



Year:	2023
Location:	Venice Architecture Biennale, Italy
Project:	BioMat Department
Typology:	Pavilion
Themes:	Bio-materials
Sources:	[University of Stuttgart]
Case study ID:	016



University of Stuttgart

itke

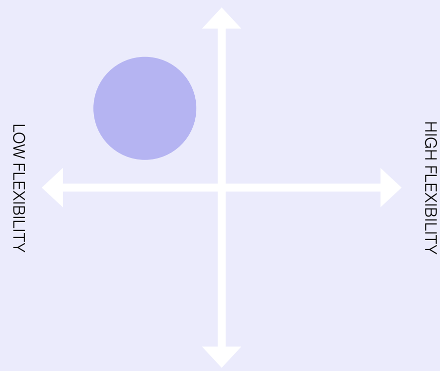
TO GROW A BUILDING

Totem

To Grow a Building is a research-driven project exploring sustainable architecture through the utilization of 3D-printed structures crafted from locally sourced soil and plant seeds, allowing the seeds to germinate and grow after printing. The roots intertwine within the structure, providing natural reinforcement and strength, reducing the need for traditional building materials.

The project aims to combine the precision of digital fabrication with the natural adaptability of plants, contributing to sustainability and the preservation of local plant species. This innovative method was tested by creating a totem-like structure with different geometries and seed types, which was placed in a garden setting where the plants grew, some even reaching harvestable heights.

Year:	2023
Location:	Tel Aviv, Israel
Project:	Nof Nathansohn, Elisheva Gillis, Yuval Ayali, Gitit Linker
Typology:	Building components
Themes:	Local materials, living materials
Sources:	Nof Nathansohn
Case study ID:	017



TOTEM DESIGN TEAM: NOF NATHANSOHN, ELISHEVA GILLIS, YUVAL AYALI, GITIT LINKER
BOTANICAL TEAM: TOMER FARAJ, DIKLA LIFSHITZ, EINAV MAYZLISH-GATI.

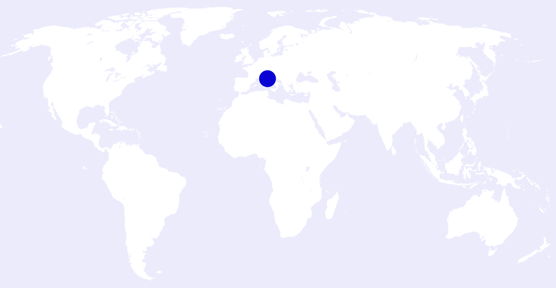
IMAGES BY NOF NATHANSOHN

TECLA

House 3D printed with local soil

TECLA is a fully 3D printed housing unit that integrates traditional building techniques with natural, locally sourced materials. Designed by Mario Cucinella Architects (MCA) and engineered by WASP, it uses recyclable materials from the local soil, making it carbon neutral and adaptable to different climates.

The double-dome design combines structure, roof and cladding to ensure efficiency. It was built using two synchronised 3D printers, using automation protocols to optimise movement and efficiency. The soil mix was tailored to local climatic conditions, with solar analysis and computational tools guiding the design to improve thermal performance and energy efficiency. (Chadha, et al., 2024)



Year:	2021
Location:	Massa Lombarda, Italy
Project:	Mario Cucinella Architects
Typology:	Housing
Themes:	Traditional materials, bio-materials, local materials
Sources:	WASP
Case study ID:	018

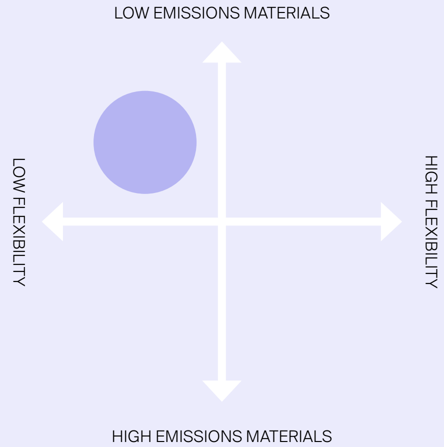


IMAGE BY WASP

CHADHA, K., DUBOR, A., CABAY, E., TAYOUN, Y., NALDONI, L., & MORETTI, M. (2024). ADDITIVE MANUFACTURING FOR THE CIRCULAR BUILT ENVIRONMENT: TOWARDS CIRCULAR CONSTRUCTION WITH EARTH-BASED MATERIALS. IN A CIRCULAR BUILT ENVIRONMENT IN THE DIGITAL AGE (PP. 111-128).

mca mario cucinella architects

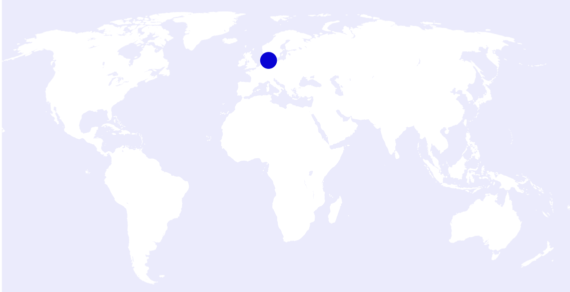
REEFCIRCULAR

Turning shell waste into sea life

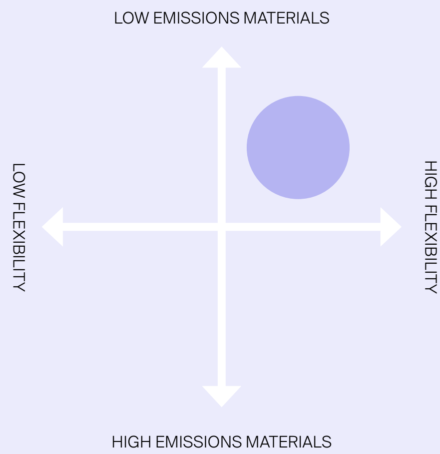
ReefCircular is dedicated to restoring marine ecosystems transforming shell waste into 3D printed artificial reef structures designed to mimic natural habitats.

The ReefKasse system, a modular artificial reef tile, can be easily installed on harbour walls and underwater structures, providing an ideal surface for marine organisms to attach and grow, helping to counteract habitat loss in urban coastal areas.

In Hundested, Denmark, 24 artificial reef tiles have been installed to create complex habitats for small fish, seaweed and invertebrates on seawalls and seafloor. The installation process is efficient, taking as little as 30 minutes and requiring no dive teams, making it an accessible solution for biodiversity restoration. The system is currently being tested in clay, which has lower CO_2 emissions than concrete, and will be available in shell-based bio-concrete from 2026.



Year:	2024
Location:	Hundested, Denmark
Project:	ReefCircular
Typology:	Environment
Themes:	Circularity, bio-materials, traditional materials, system
Sources:	ReefCircular
Case study ID:	019



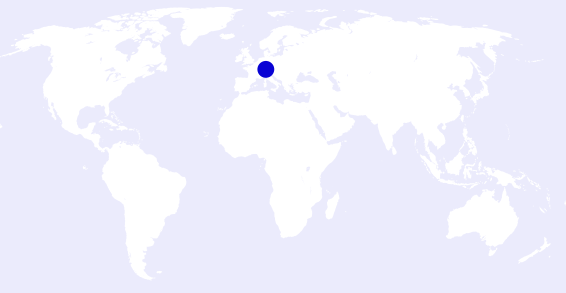
IMAGES BY REEFCIRCULAR AND ANEMO ROBOTICS

AIRLEMENTS

Insulated Walls with Sustainable Mineral Foam

Airlements project, developed by researchers at ETH Zürich in partnership with FenX AG, employs large-scale robotic 3D printing to create monolithic, lightweight, and insulated wall systems using cement-free mineral foam crafted from recycled waste.

This innovative material, with varying densities, optimizes thermal performance and energy efficiency, reducing operational energy needs for heating. The Airlements prototype showcases rapid, low-energy 3D printing, each 25 kg hollow segment hardening over a week without energy-intensive processes. The technology's versatility allows for non-structural exterior walls and seamless integration of reinforcements.



Year:	2023
Location:	Zürich, Switzerland
Project:	FenX, ETH Zürich
Typology:	Building components
Themes:	Circularity, energy efficiency
Sources:	[ETH Zürich - DBT]
Case study ID:	020

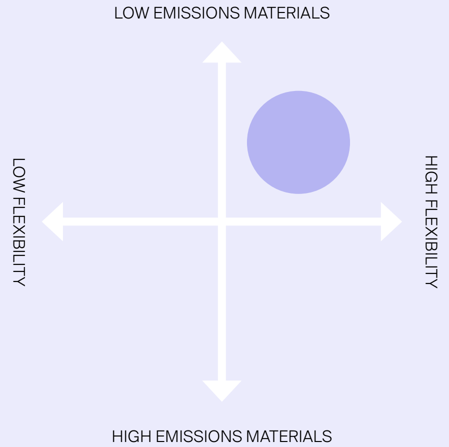
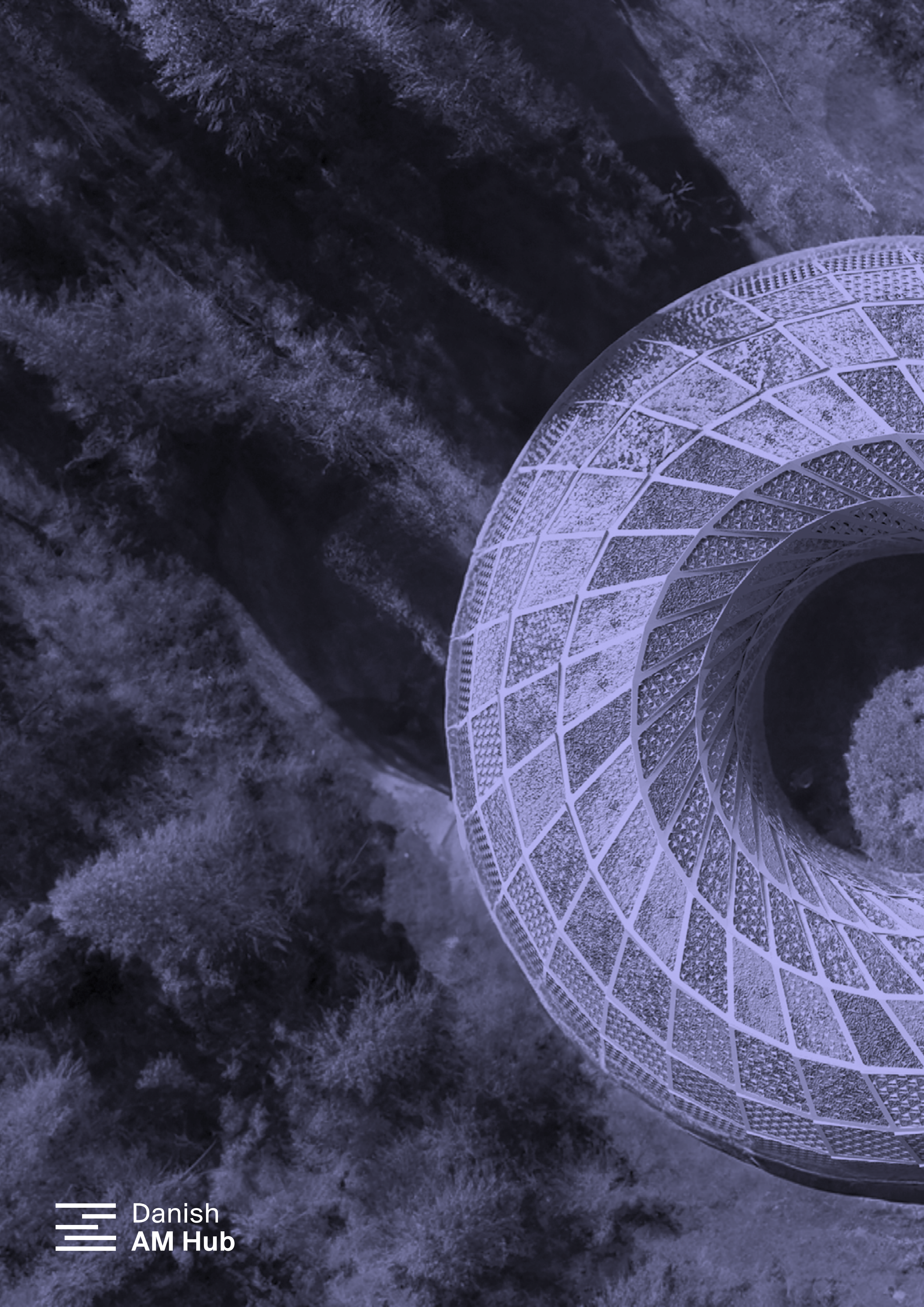
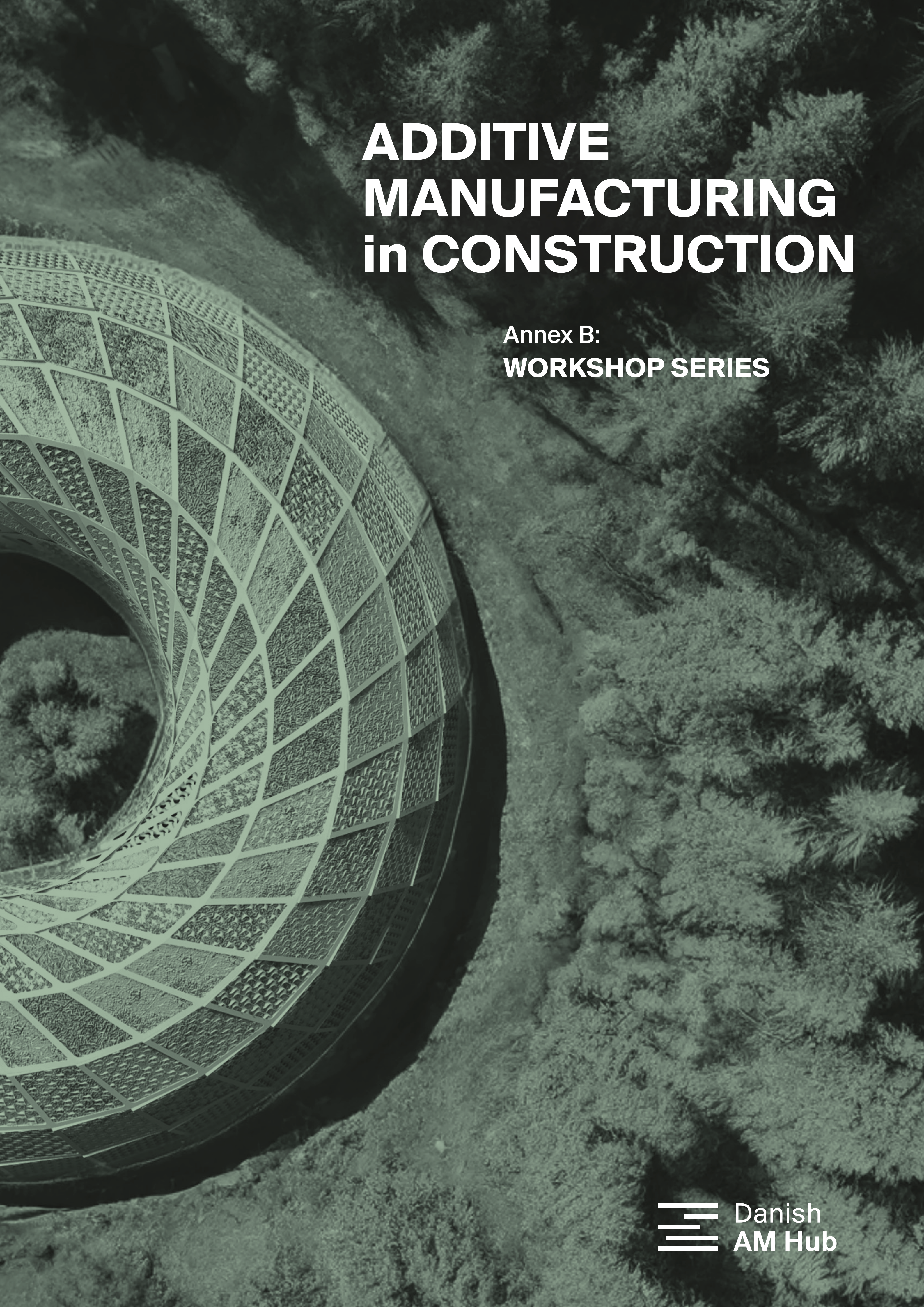


IMAGE BY: PATRICK BEDARF, DIGITAL BUILDING TECHNOLOGIES, ETH ZURICH

BEDARF, P., JEOFFROY, E., DILLENBURGER, B. (2023) AIRLEMENTS: A LIGHTWEIGHT AND INSULATING MONOLITHIC WALL SYSTEM MADE WITH MINERAL FOAM 3D PRINTING. IN: PROCEEDINGS OF THE 43RD ANNUAL CONFERENCE FOR THE ASSOCIATION FOR COMPUTER AIDED DESIGN IN ARCHITECTURE (ACADIA).

ETH zürich dbt Digital Building Technologies FenX


Danish
AM Hub



ADDITIVE MANUFACTURING in CONSTRUCTION

Annex B:

WORKSHOP SERIES

Danish
AM Hub

Danish AM Hub

WORKSHOPS

2-6 July 2023
UIA
What is the interest for AM?

27 September 2023
WS 1:
AM and the challenges in AEC

24 October 2023
WS2:
AM in construction
– production and execution

2 November 2023
WS3:
AM and Sustainability
@Building Green

15 November 2023
WS4:
AM and Technical Maturity,
Challenges and Technology

7 December 2023
WS5:
Design and Materials for AM

18 January 2024
WS6:
Conference

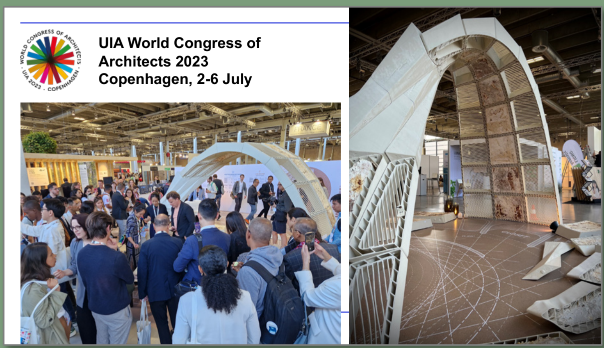
WORKSHOP SERIES:

circa 100 participants from

- ARCHITECTURE
- CONTRACTORS
- ORGANISATIONS
- COMPANIES
- ENGINEERING
- RESEARCH

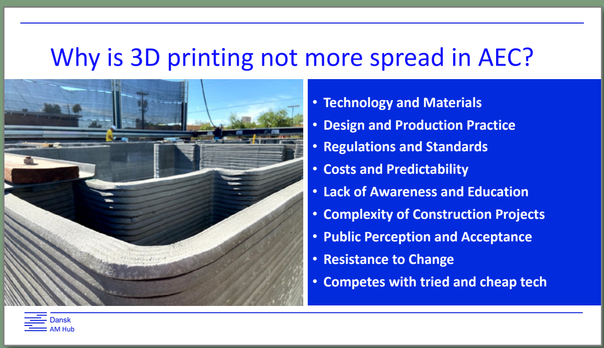
www.am-hub.dk/construction

WHAT HAVE WE LEARNED SO FAR...



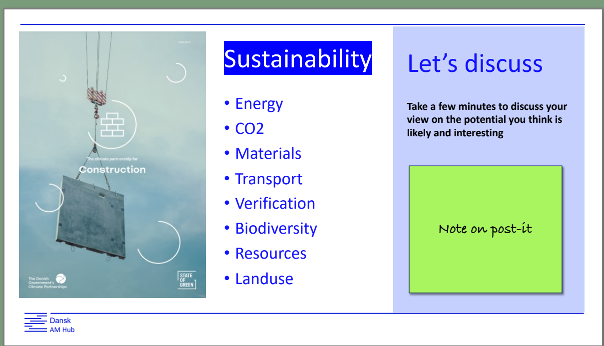
There is interest but limited knowledge.

AM can be a solution to many challenges in AEC.

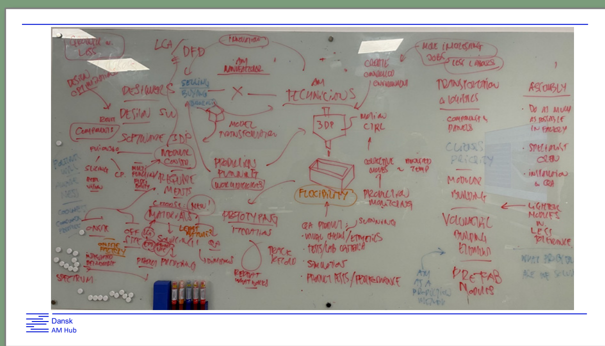


There are substantial barriers.

There are many cases.



AM can increase sustainability.



The process and the tech is there but they need maturity.

Danish AM Hub

WORKSHOP 0

“Sustainable Construction and Additive Manufacturing”

Dialogue and short interviews with the participants.

Topic:	What is the interest for AM?
Date:	2-6 July 2023
Location:	UIA World Congress of Architects 2023, Bella Center, Copenhagen

MAIN OUTCOMES:

- There is an interest in AM for architecture and engineering, but limited knowledge on potential and use.
- AM is mainly know as a structural onsite concrete solution, with limitations.
- Application is known for new smaller buildings with unique architecture.
- The maturity and sustainability aspects of AM need to be futher explored to be able to scale AM in the construction industry.
- Interesting to explore AM application in combination with biogenic materials.

WORLD CONGRESS OF ARCHITECTS · UIA 2023 · COPENHAGEN

WORKSHOP 1

"Sustainable Construction and Additive Manufacturing"

PROGRAM:

- Introduction Danish AM hub
- Challenges in the construction sector & AM opportunities
- Case studies:
  - Andrea Hektor, Director, BIG Engineering
  - Matúš Uríček, CTO, Co-founder, WOHN A/S
- Workshop and discussion

AEC CHALLENGES

Labor Shortages	Project Delays	Supply Chain Disruptions	Quality Control	Economic and Political Factors
Cost Overruns and Budget Constraints	Safety and Regulatory Compliance	Sustainability and Environmental Concerns	Technology Integration	Complex Project Management

Topic: AM and the challenges in the architecture and construction industry

Date: 27 September 2023

Location: Danish AM Hub

SOME OF THE CURRENT CHALLENGES THAT AM CAN ADDRESS:

- Design flexibility and optimization
- Use of new materials
- Production speed, process optimization and adaptability
- Reduced waste and CO_2

BARRIERS TO SCALE:

- Lack of competence and methodogy
- Immature tech stack and standards
- Limited amount of good cases and results (eg. perception, cost/business model and LCA)

WORKSHOP 2

“Sustainable Construction and Additive Manufacturing”

PROGRAM:

- Introduction to the project Eleonora Orsetti, Programme Director Dansk AM-Hub
- AM in construction - benefits and barriers to adoption, Niels Falk, Partner HD Lab
- 3D construction printing – the COBOD experience, Alma Bangsgaard Svendsen, Architect and Project Manager at COBOD International
- Site visit - construction site in Brøndby3DCP Group

Topic:	AM in construction – production and execution
Date:	24 October 2023
Location:	Danish AM Hub + 3DCP Group construction site in Brøndby

MAIN OUTCOMES:

- About 40% of a building can be 3D printed
- Currently the AM practice is focused on concrete building shells
- Reservations are experience from clients and architects regarding the look and benefits
- Mostly employed for experimental designs and small scale
- There is not a lot of capacity and most projects are ”hand held” and require finishing

WORKSHOP 3

"Sustainable Construction and Additive Manufacturing"

PROGRAM:

- What is AM for construction?
  - Intro to AM and pro/cons
  - Challenges in construction
  - Cases AM in construction X4
  - Other use cases
- Debate sustainability and AM: Potential – effect and adoption
- What is next: Discussion of breaking barriers

Topic: AM and Sustainability

Date: 2 November 2023

Location: Building Green, Forum Copenhagen

THE BENEFITS OF USING AM:

- **New and more sustainable materials and composites – potential reuse**
- **Optimization of design and less use of materials**
- **Less waste and transport – Lower CO_2 emissions**

WORKSHOP 4

"Sustainable Construction and Additive Manufacturing"

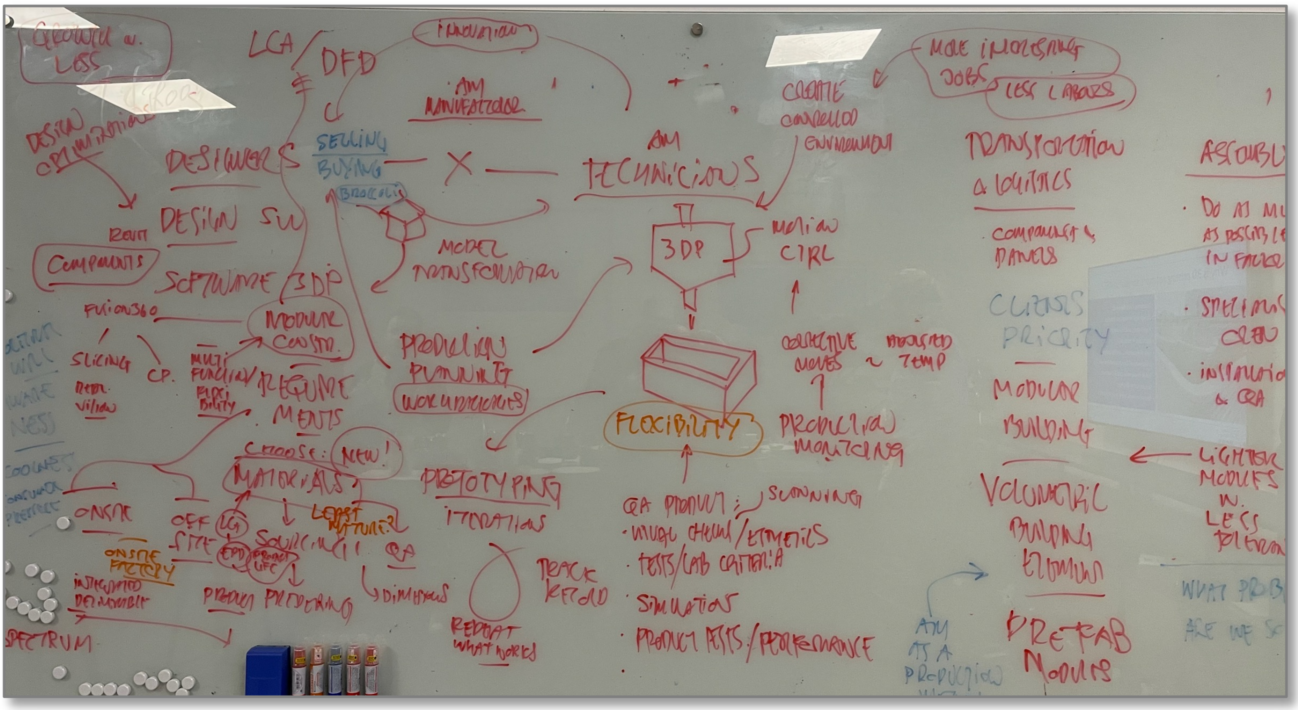
PROGRAM:

- Construction AM Tech Stack
- Maturity and availability of AM Tech
- Conversation with selected experts on AM, digital technology and architecture

Topic:	AM and Technical Maturity, Challenges, and Technology
Date:	15 November 2023
Location:	HD Lab

MAIN OUTCOMES:

- The AM for construction tech stack is still immature
- The printing technology and software is well developed from other industries
- AECO methods, tools and data is spares
- The is no DfAM or DfSAM methodlogy and no tool support
- The first ISO standard for AM in construction has just been relased at the end of 2023



WORKSHOP 5

“Sustainable Construction and Additive Manufacturing”

PROGRAM:

- Introduction to the project, Eleonora Orsetti, Programme Director Dansk AM-Hub
- Additive Manufacturing processes for Architectural Design, Katie Heywood, Industrial PhD fellow at Henning Larsen & Royal Danish Academy
- Stress-based design for 3D concrete printed horizontal structures, Luca Breseghello, PhD Candidate at CREATE at the University of Southern Denmark
- New design tools and generative design, James Walker, Senior Design Specialist, HD Lab
- Group talk: Where can we focus with AM? What’s next?

Topic:	Design and Materials for AM
Date:	7 December 2023
Location:	Danish AM Hub

MAIN OUTCOMES:

- More knowledge and maturity in the value chain
- Close the gaps in the processes in construction
- Improve esthetics of 3D-printed solutions
- Explored LCA and durability of AM
- More verified projects – scaled AM
- Logistics for AM at the construction site
- Development and spread of AM design tools and systems
- More providers and small suppliers
- Higher availability of printers and experts
- Improved financial muscle for being “first mover”
- More cross industry learning
- More talent and innovation in AECO

WITH THE CURRENT CHALLENGES AND MATURITY, WHERE SHOULD WE START TO SCALE WITH SUCCESS:

- Facade systems, interior designs and walls, structural components e.g. beams and slabs
- Components optimized, generic to specific design and produced off-site
- New materials in components
- Onsite production adaptive design flexibility e.g. joints, renovation and circular building

Danish AM Hub

WORKSHOP 6

"Sustainable Construction and Additive Manufacturing"

PROGRAM:

- Presentation of the project and main results
- Alma Bangsgaard Svendsen, Architect and project manager at COBOD International
- Christian Thuesen, Associate Professor, Department of Engineering Technology and Didactics Building Technology and Processes at DTU - Technical University of Denmark
- Katie Heywood, Industrial PhD fellow at Henning Larsen & Royal Danish Academy
- Matúš Uríček, Co-Founder and CTO at WOHN A/S
- Discussion
- Conclusion and recommendations

Topic:	Final Conference
Date:	18 January 2024
Location:	BLOXHUB

FOCUS AREAS

- **Area 1:**
  Building level - large scale
  Recycled or innovative materials
- **Area 2:**
  Building level - large scale
  Conventional materials
- **Area 3:**
  Component level - small scale
  Recycled or innovative materials
- **Area 4:**
  Component level - small scale
  Conventional materials

MAIN BARRIERS FOR AM ADOPTION:

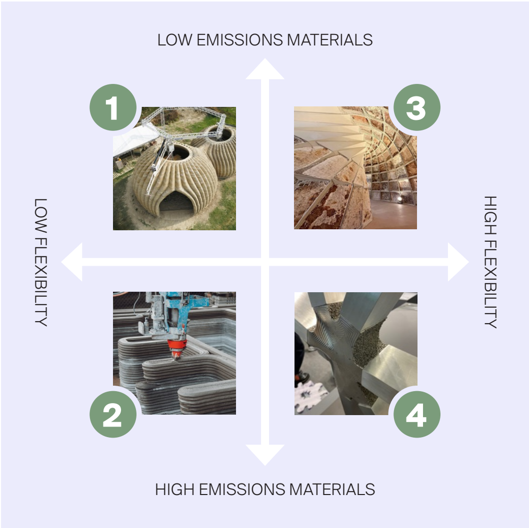
- Aesthetic
- Lack of a broad and quick adaptation in a conservative industry
- Siloed focus on AM
- Legislation
- Sustainability
- Lack of investments

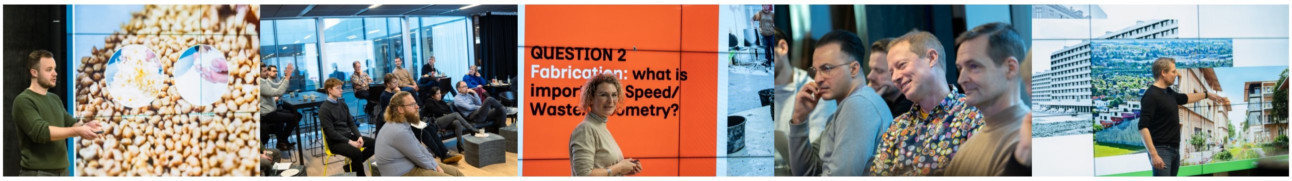
KEY STAKEHOLDER FOR AM ADOPTION:

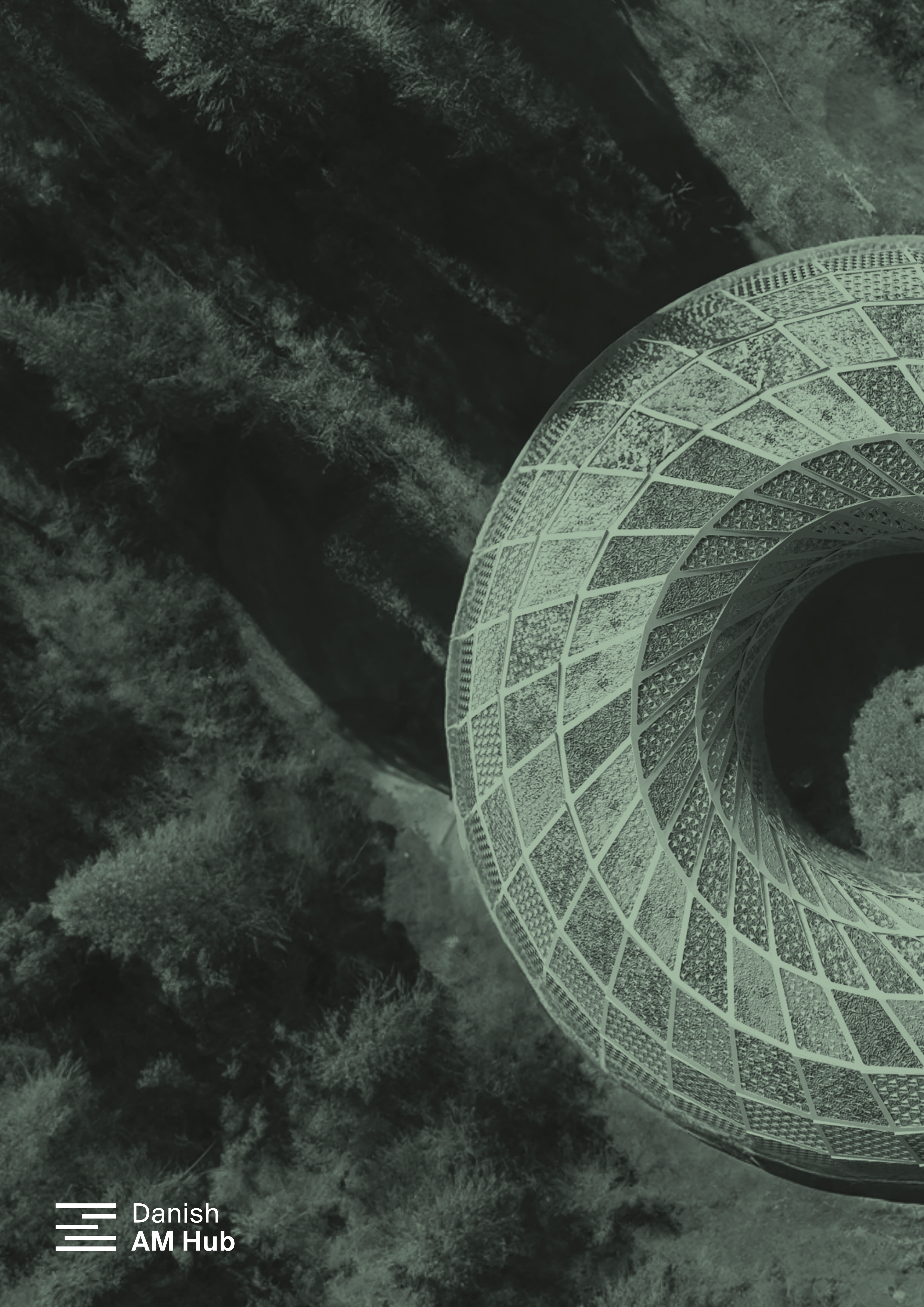
- Contractors
- Investors
- Regulators

FOCUS ON:

- Component level
- Sustainable materials



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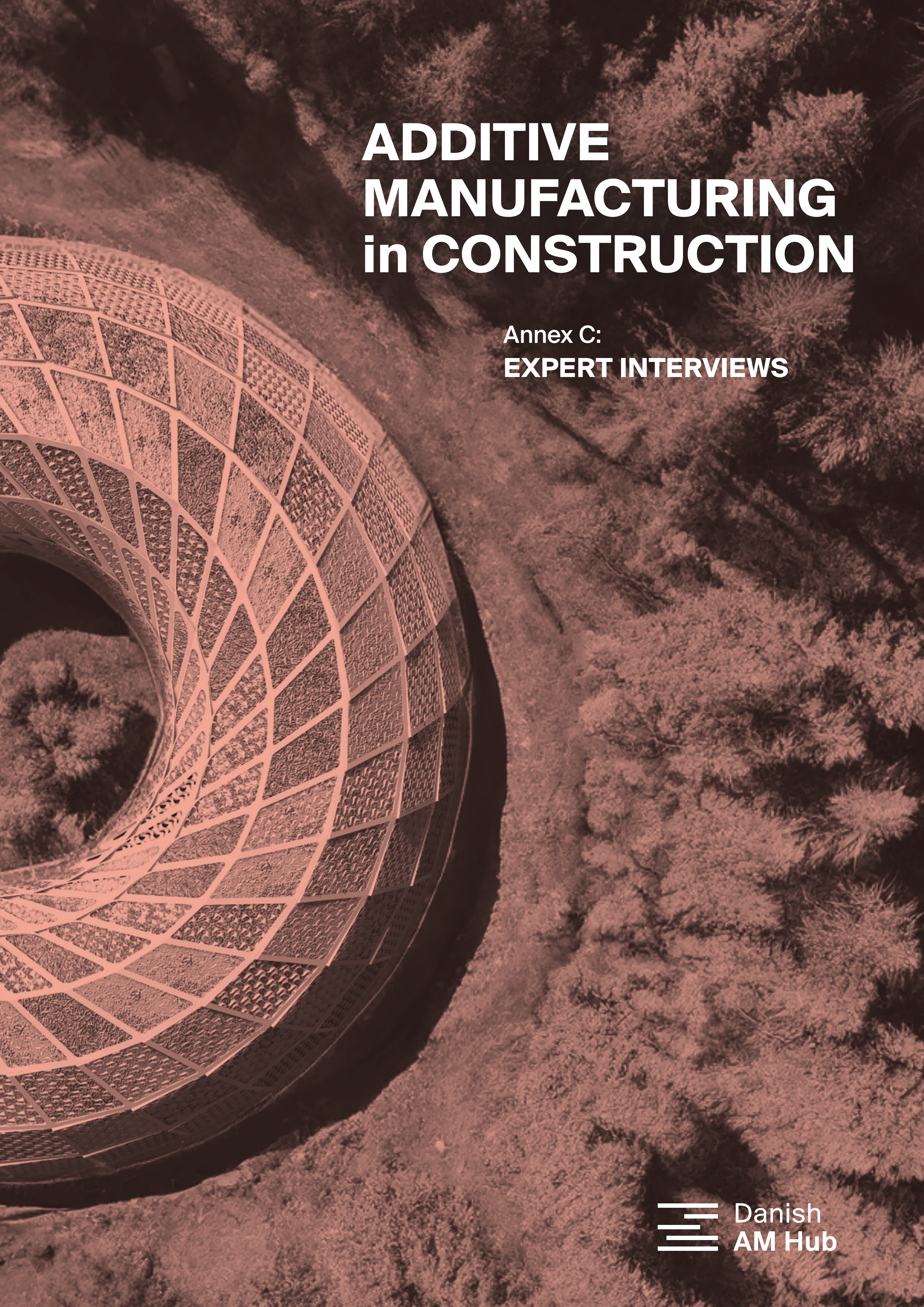
ADDITIVE MANUFACTURING in CONSTRUCTION

Annex C:

EXPERT INTERVIEWS



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EXPERT INTERVIEWED

Artemis Antonopoulou
Workshops & Project Manager at Trifolium

Andrea Ling
Digital Building Technologies
Institute of Technology & Architecture, ETH Zurich

Hedwig Heinsman
Co-founder & Creative Director at Aectual

Jörg Petri
Founder & Architect at NDC

Kathryn Larsen
Founder & Architect at Studio Kathryn Larsen
and ReefCircular

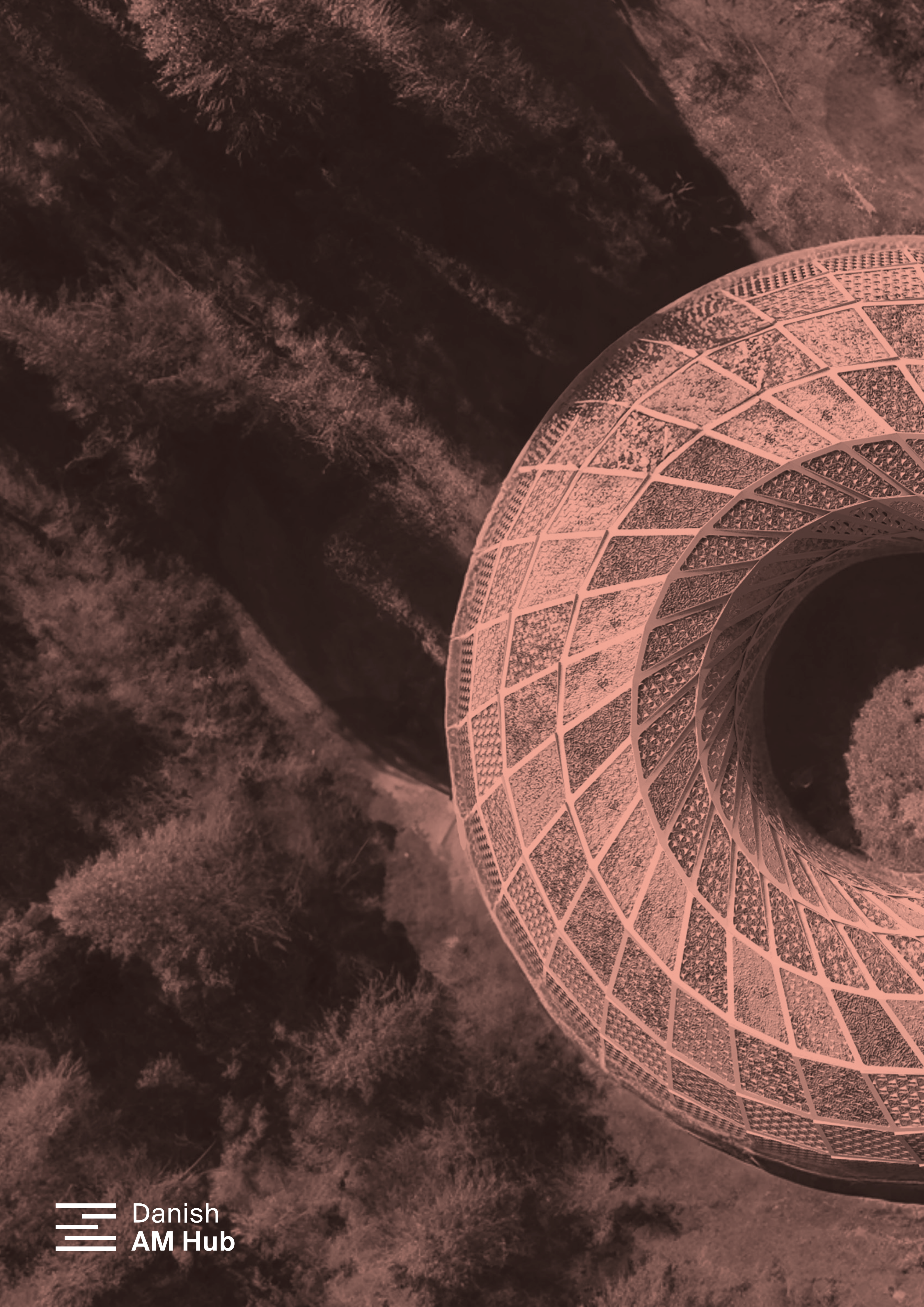
Nicolas Ramirez Ortiz
Industrial PhD student, University of Southern Denmark
Founder at Precious Plastic

Mathilde Marengo, Head of Studies
& **Alexandre Dubor** - Architect, Engineer
Institute for Advanced Architecture of Catalonia

Paraskevi Vardaka
Dutch Invertuals

Samim Mehdizadeh
PhD student at TU Darmstadt

www.am-hub.dk/construction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