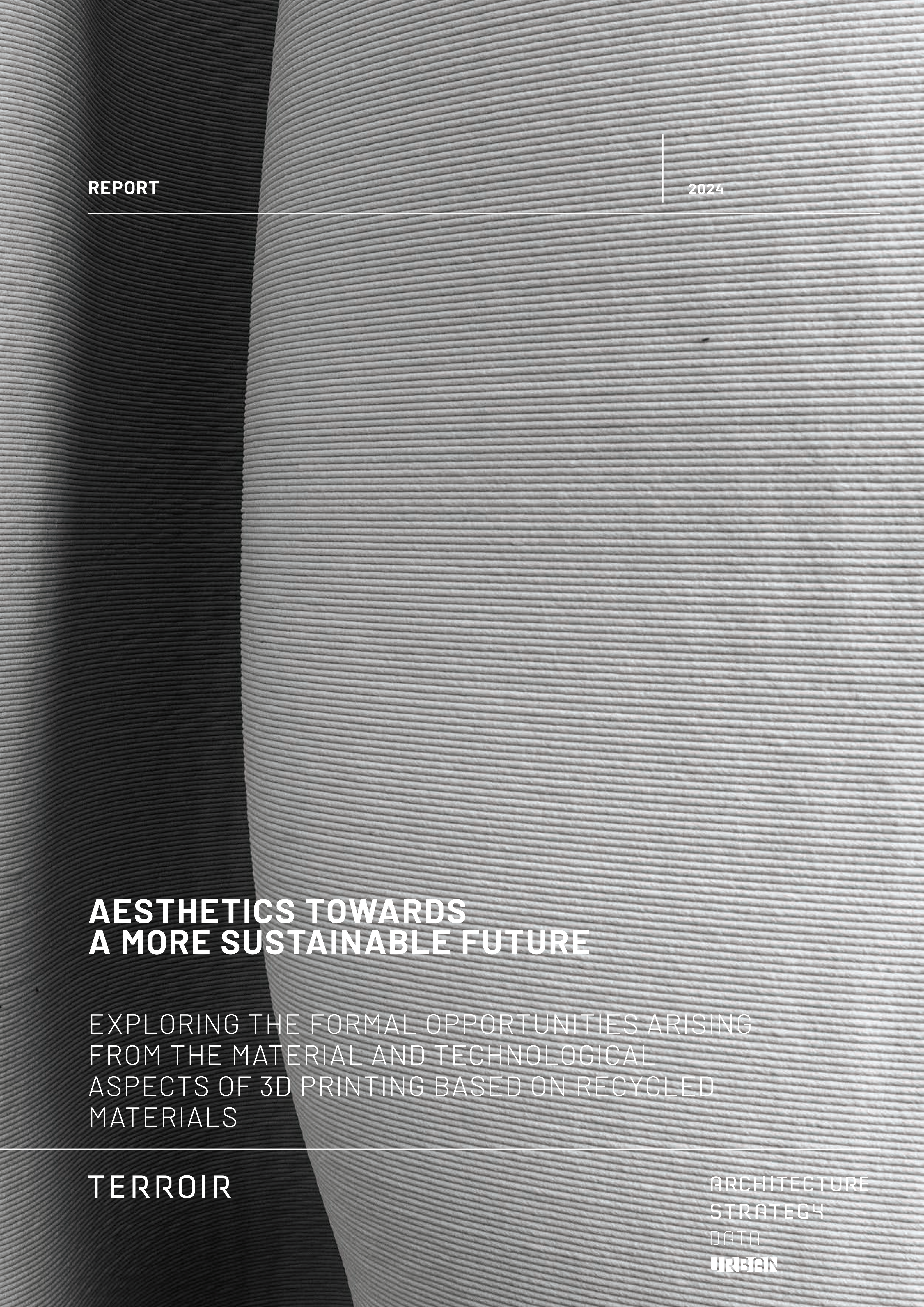


REPORT

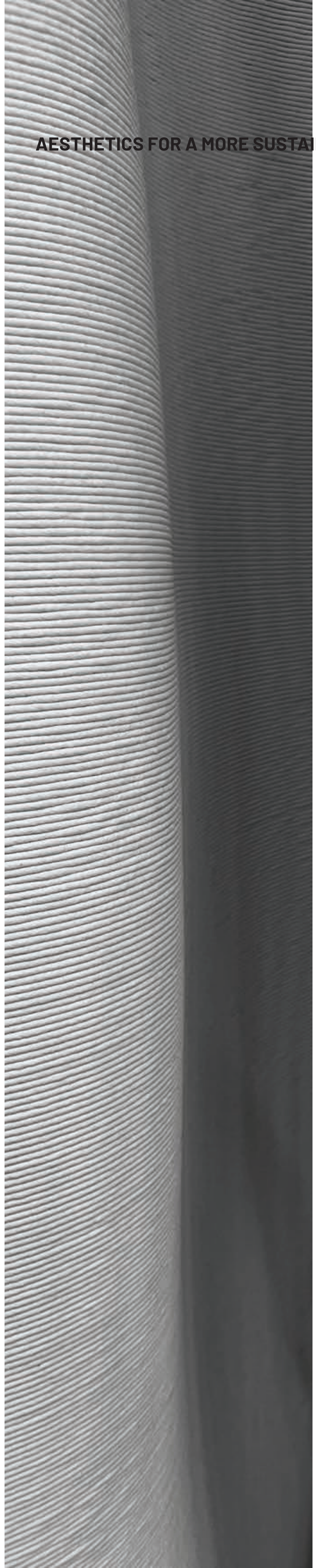
2024

AESTHETICS TOWARDS A MORE SUSTAINABLE FUTURE

EXPLORING THE FORMAL OPPORTUNITIES ARISING FROM THE MATERIAL AND TECHNOLOGICAL ASPECTS OF 3D PRINTING BASED ON RECYCLED MATERIALS

TERROIR

ARCHITECTURE
STRATEGY
DATA
URBAN



WOHHN
Herlufmagle

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HOMES AS A SERVICE

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> **“This research aims to challenge the conventional understanding of the relationship between craftsmanship, aesthetics, and materials that characterises the current discussion on sustainable construction in the architecture and building industry.**
>
> **Making this challenge initiates possibilities for a radically decarbonised form of building enclosure.”**

- Terroir, Aesthetics for a more sustainable future

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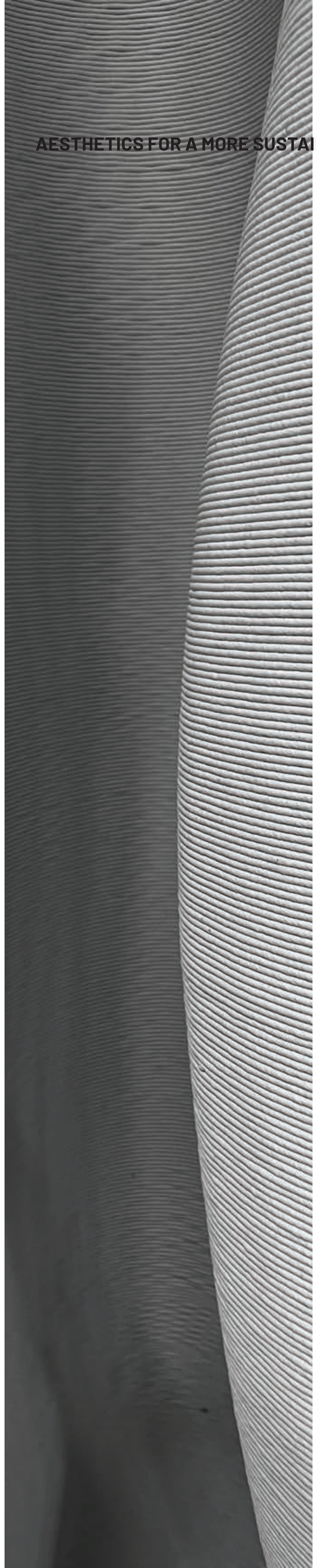

WOHN
Herlufmagle

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THE QUESTION OF PLACE

With the acceleration in finance and technology since the 1990s, a question that once underpinned architectural discourse - that of its relation to place - was banished.

“Place” as an issue of central concern was considered quaint in relation to the potential of technology such as robotics and advanced fabrication processes, and in turn the potential for radical formal experimentation took centre stage as the disciplinary question of main concern.

So why is this study different? The dilemma in this focus on formal experimentation was often an exercise in simply exploring the formal and aesthetic potentials of new technology to an end in itself. This ever accelerating focus on the growth of formal potentials in parallel with a seemingly unstoppable growth of financial resources had no logical transition until perhaps the onset of COVID.

We can now reflect on writings published just prior to March 2020 (the Uninhabitable Earth, Adaptation and others) and the deep questioning in society around growth values that has occurred in the wake of COVID.

That COVID is a sort of pivot point in contemporary discourse can perhaps be attributed to the fact that the pandemic is the clearest after-effect we have yet experienced in regard to climate change and the impacts of degradation of places and habitats of both people and animals.

This realisation that place disturbance or change can literally make an entire planet sick has radically changed the disocurse. Place (with a capital P) contains the wicked problems of today, incl. climate change and the need for decarbonization, social inequality and affordable living, global demographic changes and the changes in living and labor.

With the planet now unable to provide appropriate environments for the many animals and plants that have gone extinct over the past two decades, and for the people that have had to migrate to safer locations over the same period, a renewed interest in the planet and its places has emerged in architecture while fuelling additional consumption through those tools used to promote it.

Morning mist, Rock Island Blend
Peter Dombrovskis

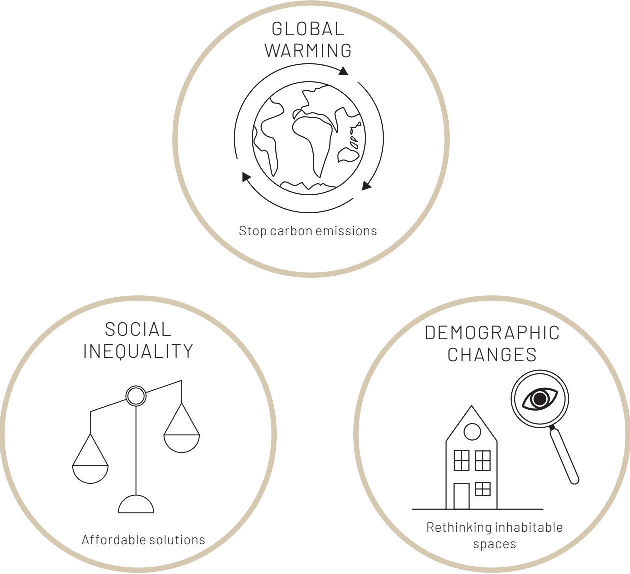


Figure:1.B

SUSTAINABILITY TOOLS, CARBON INCREASES

The outsourcing of sustainablity in the early 2000s to calculation tools that focused on energy consumed rather than energy embodied not only had no impact on carbon emissions, they actually increased.

When sustainability first became a major issue or discussion in the 1990s, various countries invented ratings tools to measure energy consumption - LEED (in the US), Green Star (in Australia), DGNB (in Germany) and so on.

However, in measuring energy consumption (and in often primitive ways) we in fact accelerated global carbon emissions over the past decades such that in the last 30 years we have emitted more carbon into the atmosphere than in the entire history of human occupation of the planet before then.

That is, the industry worked out how both to promote sustainability while fuelling additional consumption through those tools used to promote it.

Moving forward to the present, we have an equally strident focus on new tools, now ones that calculate embodied carbon. While more sophisticated and effectual than the first wave, the focus remains on abstract forms of calculation, generally disembodied and considered separately to places or people. As a result, we are seeing a rush to use mass timber in most countries, for example, a rush that fails to question the sustainable of an industry focused in southern Germany and Austria. The buildings they produce use not only imported timber but reduce carbon by only 10% or so. A new building is still building, in the end.

Figure:1.C

LEED, Green Star & DNGB
Ratings tools measuring; energy consumption

MATERIALS FOR A MORE SUSTAINABLE FUTURE

A conclusion we reached in the mid-2000s, and now borne out via the emissions of the intervening 20 years, is that sustainability is in fact an aesthetic issue.

Why aesthetics? We now understand that true decarbonisation requires radical transformation and material re-use and, when new materials are introduced, radically new formal potentials. In both cases, the aesthetic outcomes of these explorations form a break with 2000 years of agreement regarding the question of beauty.

By focusing on aesthetic matters, we have the opportunity to move past the "new building" as the only culturally preferred vehicle for sustainable building.

We need to explore different aesthetic histories that address the fragment, the unfinished, the weathered and the incomplete, as a means of truly approaching the conditions for a sustainable architecture.

Concept such as "clarity", "completeness", "harmony" and so on, do not map onto the aesthetic implications of repair. Similarly, they do not necessarily reconcile with the opportunties afforded by new material types and manufacturing processes.

Plastic pavillion
Copenhagen

NEW MATERIALS, NEW AESTHETICS

The need to find ways of decarbonising the construction industry has seem two key poles emerge. One is understood as an approach based in "repair". That is, the continued use of something existing through processes of repair and minor replacement or renewal. The other is a search for new materials and fabrication techniques. It is this second strategy that is the subject of this report.

As the world grapples with the urgent need to reduce carbon emissions and combat climate change, industries are seeking innovative ways to lower their environmental footprint. One such sector facing a significant challenge is the building industry. 3D printing offers significant advanteges however this also engenders novel advantages.

While 3D printing has revolutionized manufacturing and design processes, it also poses environmental concerns due to its reliance on traditional plastics and energy-intensive production.

The dilemma lies in the fact that 3D printing, often hailed for its efficiency and customization capabilities, is paradoxically contributing to pollution and resource depletion. The conventional materials used in 3D printing, such as petroleum-based plastics, generate substantial carbon emissions during their production and disposal phases. Additionally, the energy requirements for 3D printing processes, particularly in large-scale manufacturing, can be considerable.

To address this dilemma, there is a growing imperative to find new materials that are both sustainable and suitable for 3D printing. Researchers and innovators are exploring alternative materials derived from renewable sources, like bioplastics and recycled polymers. These materials have the potential to reduce the carbon footprint of 3D printing significantly. Because they employ material that no longer serves a function.

Furthermore, the need for more energy-efficient 3D printing technologies and processes is pushing the industry to develop greener solutions. Companies are investing in research to create printers that consume less energy, and optimize production cycles to minimize waste.

To ensure widespread adoption of the technology, these technological refinements need to be explored in parallel with the question of aesthetics. This entails not only advancing the capabilities of 3D printing but also examining how these advancements align with and enhance the visual and spatial aspects of architectural design.

Recognizing their interconnectedness and advocating for their simultaneous consideration in the pursuit of a low-carbon future where aesthetic spatial qualities are integral to construction practices.

This study seeks to bring together these two fields—technology and aesthetics—in the interest of working toward a low-carbon future where aesthetic spatial qualities play a central role in construction.

To achieve the most comprehensive research, we initiated a collaboration between the Australian/Danish architecture firm Terroir and the Danish 3D printing company WOHN. Both are experts in their respective fields, with Terroir specializing in architectural aesthetic spatial comprehension, and WOHN focusing on technology management and printing.

ZOOM; PLASTIC PAVILION
The seam where two surfaces meet

POTENTIALS OF 3D-PRINTING

THE POTENTIAL OF 3D PRINTING STIMULATES A BROAD SPECTRUM OF QUESTIONS, SIGNIFICANTLY IMPACTING THE DISCOURSE ON ARCHITECTURAL AESTHETICS GIVEN THE TECHNICAL, MATERIAL AND STRUCTURAL CHARACTERISTICS OF THE MATERIAL.

INTRODUCTION

Charting the possibilities offered by 3D printing sketches a vision for the future trajectory of the construction industry.

For this trajectory to take hold, we need to challenge the conventional understanding of the relationship between craftsmanship, aesthetics, and materials that characterizes the current discussion on sustainable construction in the architecture and building industry. In making this challenge, we can simultaneously make space for opportunities for a radically decarbonised form of building enclosure.

REPORT METHODOLOGY //

This report documents the research project, "Aesthetics towards a more Sustainable Future: Exploring the formal opportunities arising from the material and technological aspects of 3D printing based on recycled materials." Initiated in 2022, the project has progressed through 2023 and 2024, resulting from a collaboration between TERROIR and WOHN.

PROJECT PARTICIPANTS //

TERROIR is an Australian/Danish architectural practice and WOHN is a Danish 3D printing company. Both are experts in their respective fields.

The report consolidates all information and knowledge acquired during this collaboration into a systematic overview, describing the technology, its functionality, the potential it harbors, and prospective scenarios for its future application.

The purpose of this report is not to act as a manual for printing large-scale 3D structures but to explore the various facets of large-scale 3D printing, using the Wohn product as a case study. Therefore, this document serves as a record of the current knowledge on the subject, intended to support ongoing exploration and study. Concurrent with the report, a series of physical 3D printed elements have been developed.

While there are overlapping concepts, ideas, and questions between the report's content and the design of these elements, they are considered two distinct and somewhat independent tracks.The subsequent paragraphs present the original project description to provide the reader with insight into the project's inception and the context of this report.

ORIGINAL PROJECT OVERVIEW //

By conducting concrete design and material investigations, we will present ways to work with a familiar but underutilized technology in the construction industry - circular large scale 3D printing. By testing the possibilities and limitations of large scale 3D printing technology, the project will challenge current assumption about the formal and material repertoire for a more sustainable architecture. Our thesis is that new formal and spatial possibilities arise when a fully recyclable material composition is assembled through large-scale 3D printing.

RESEARCH SCOPE AND OBJECTIVES //

To understand the haptic, sensory, and spatial potentials of the material and its production methods, the explorations will be conducted through an iterative process involving the design and production of a series of physical elements at multiple scales. This iterative process allows for the investigation of numerous aspects, such as the material's morphological and plastic properties, surface treatments, structural characteristics, assembly systems, haptic and sensory characteristics, production principles, and much more.

Within the context of WOHN, its industry segment and their ambitions to rethink the understanding of "building". The following nine key concepts, anchors the project and how 3D printing may contribute to a more sustainable industry, as listed opposite:

Figure:2.A

AUTOMATION //

Transitioning to robotic workflows in the construction industry significantly diminishes the necessity for manual labor and seamlessly incorporates various construction phases into the printing process.

Currently, the construction sector lags in adopting automated processes, presenting a substantial opportunity for evolution and enhancement. The shift towards automation promises not only to refine operational efficiency but also to elevate the quality of the resulting architectural products.

This integration streamlines the production timeline, enabling the workforce to complete structure in a single assembly setting, rather than in a fragmented way on site using numerous components shipped from elsewhere.

The transformative impact of automation, often exemplified by the automotive and computer industries, demonstrates how robotic participation is pivotal in advancing business, market, and professional landscapes.

Fabricating building components or entire structures in controlled settings mitigates the risk of construction errors. Such an environment also nullifies the impact of adverse weather conditions, a common source of project delays, failures, or complete standstills. Moreover, automation introduces the capacity for continuous operation, transcending human limitations like the necessity for rest, thereby optimizing productivity and potentially revolutionizing the construction timeline and quality.

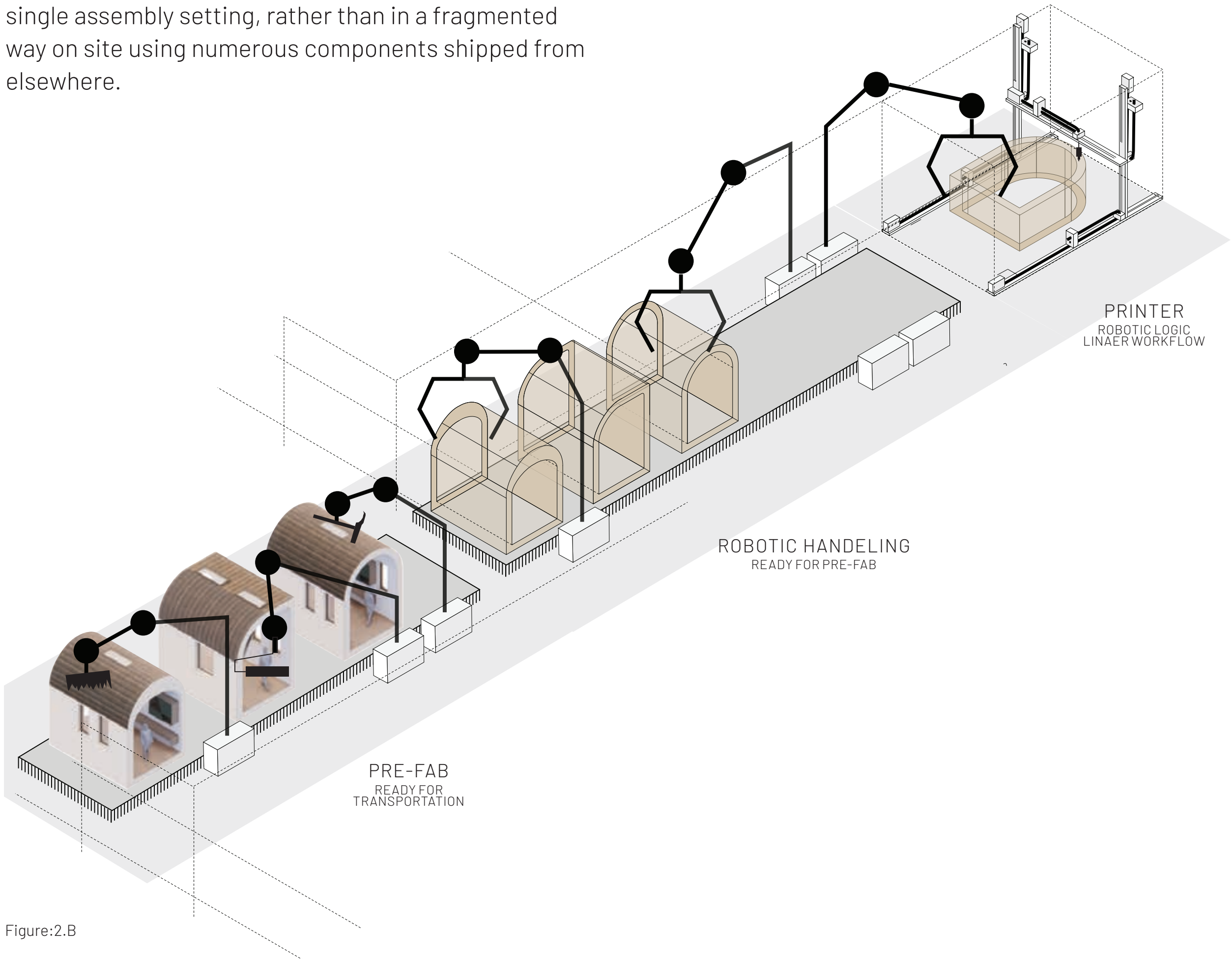


Figure:2.B

Automation; robotic workflow

MANAGEABILITY //

In addition to prefabrication, the deployment of 3D printing in construction offers substantial improvements in the manageability of construction processes when compared to traditional industry methods. Several critical aspects merit attention in this context:

1) The capability to print entire building structures or large components, integrating load-bearing elements, wall systems, and insulation within a single unit, dramatically simplifies handling and manageability. This integrated approach reduces the necessity for extensive assembly and component fitting, streamlining the construction process.

2) The reduction in the number of unique elements within a structure minimizes the time and effort required for assembly, enhancing overall manageability and operational efficiency. This streamlined approach facilitates a more organized and time-effective construction process.

3) Emphasizing prefabrication maximizes the amount of construction work completed off-site, thereby decreasing the resources needed for on-site installation and positioning. This strategy lessens the impact of adverse weather and external conditions on the construction schedule, allowing for more predictable and streamlined workflows.

By prioritizing these aspects, 3D printing and prefabrication in the construction industry present a paradigm shift towards more efficient, manageable, and controlled building processes.

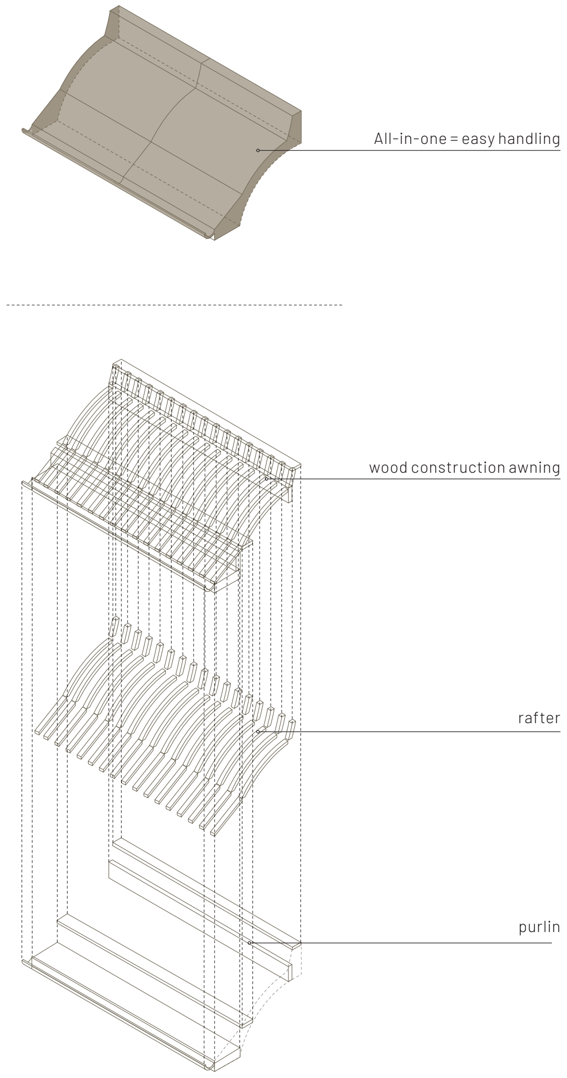


Figure:2.C

Separate elements = handling in many steps

MORPHOLOGY //

The inherent characteristics of the materials used by WOHN in 3D printing, leveraging both the robustness of wood and the malleability of plastics, when combined with the additive manufacturing capabilities of 3D printers, result in a construction methodology that offers exceptional flexibility in shaping and forming structures. This synergy enables the realization of building components that are unbound by conventional tectonic constraints.

Key to this is that 3D printing allows for the creation of complex geometries that would be difficult, if not impossible, to achieve with traditional construction methods. This capability opens up new possibilities for architectural design, where freeform structures and intricate details can be realized with precision and efficiency. It allows for the exploration of unique architectural expressions and spatial configurations, challenging traditional norms and expanding the possibilities of what can be achieved in the realm of architectural design.

The morphology of 3D printing enables the designer to tailor building elements precisely to the unique requirements and the specifics of site conditions.

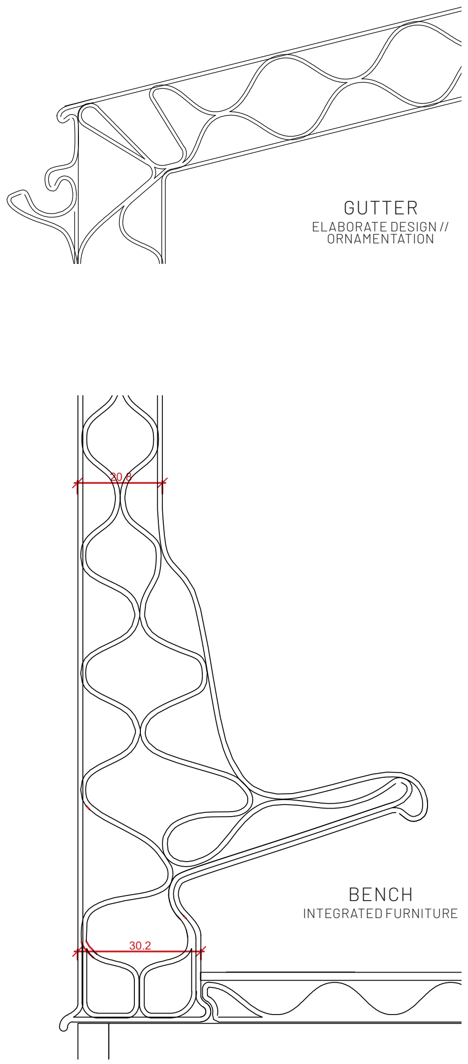


Figure:2.D
Morphlogy, tailored architecture
Sections elaborated in the Loading Parallel section, starting at page 52

ADAPTABILITY //

The precision enabled by 3D printing, particularly when augmented with technologies like LiDAR scanning that allows incredible precise site measurmeent, facilitates the creation of exceptionally adaptable solutions. Such precision ensures a customised solutions that can be precisely adapted to suit a specific contex, positioning adaptability at the forefront of design possibilities.

In the construction sector, this adaptability is indispensable for activities such as renovation or transformation, where bespoke components must be fabricated and installed with utmost accuracy. 3D printed parts can respond seamlessly and precisely to specific contextual challenges, surpassing the capabilities of standard off-the-shelf solutions.

Moreover, adaptability in 3D printing proves vital in the context of urban redevelopment and expansion. As cities evolve, the demand for integrating new constructions into existing urban fabrics increases. 3D-printed architectural components can be designed to complement the existing built fabric, facilitating seamless urban integration. This is particularly relevant in the dense urban environments where the matching of new structures with old ones requires a nuanced approach to design and construction.

This potential to optimise additive architecture in existing settings is complemented by an equally important capacity for operating in areas affected by natural disasters and which require reconstruction. For example, new homes can be made or damage structures repaired in a tailored way to respond to altered post-disaster landscapes.

This adaptability and automation can be bought together to address urgent housing and infrastructure needs that arise in the aftermath of natural disasters making 3D printing a key future technology in this sort of work.

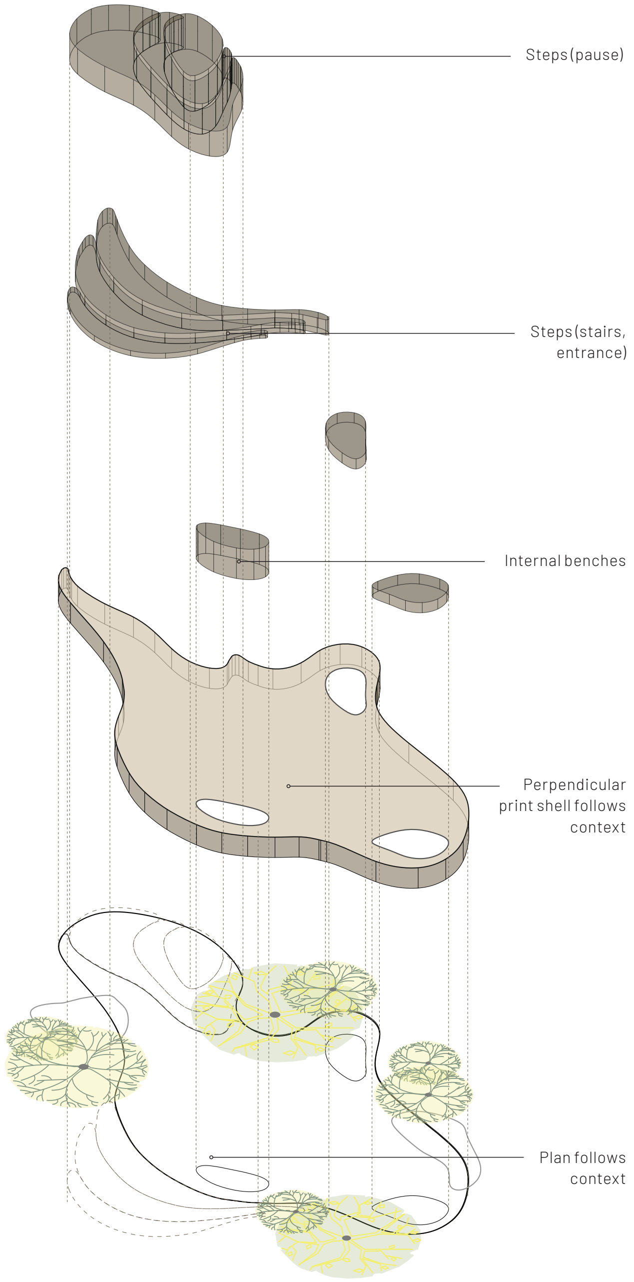


Figure:2.E
Organic plan organizarion, printed modules
Figure elaborated on page 63 (Figure:4.AF)

SCALABILITY //

Traditionally, large productions within the architectural realm may not seem particularly attractive, often associated with uniformity and lack of character. However, with the advent of 3D printing technology, large productions acquires a new dimension, enabling the delivery of high-quality architecture on a large scale, thus making exceptional design more accessible.

A conceivable approach involves utilizing a programmable script capable of adjusting to specific user requirements and preferences, allowing for the creation of architecturally coherent and spatially efficient housing solutions. The inherent capacity of 3D printers to handle complex designs without cost escalation facilitates a model of hyper-customized large productions, where individualization does not compromise efficiency or aesthetic integrity.Moreover, the scalability of 3D printing technology underscores its potential in large productions.

Theoretically, a 3D printer can operate in any location, offering the flexibility to print as needed, irrespective of the geographical context. This characteristic could significantly expedite reconstruction efforts in disaster-stricken regions, address acute housing deficits, and reclaim areas previously considered unsuitable for habitation.

By enabling the production of tailored structures on-demand, 3D printing stands to revolutionize the approach to mass production in architecture, ensuring both widespread accessibility and adaptability.

Figure:2.F
Large production, car factory

AFFORDABILITY //

The concept of affordability is pivotal in democratizing architecture, ensuring its accessibility to a broader population and also to ensuring that sustainable solutions are possible that can be afforded by a large section of the world's population. The challenge frequently encountered in the realm of design is that high-quality architectural solutions are often associated with substantial costs, thereby limiting access to a privileged few. 3D printing technology presents a unique opportunity to reconcile exemplary architectural quality with affordability.

This cost-effectiveness arises from a dual strategy employed by the material: the utilization of recycled or surplus materials, which not only reduces costs but also adheres to sustainable resource use principles, and the implementation of automation, which considerably diminishes the dependence on manual labor. These elements—resource management and labor optimization—are poised to gain even more significance in the future, given the anticipated increase in scarcity of naturally extracted resources, coupled with a projected decline in the working population.

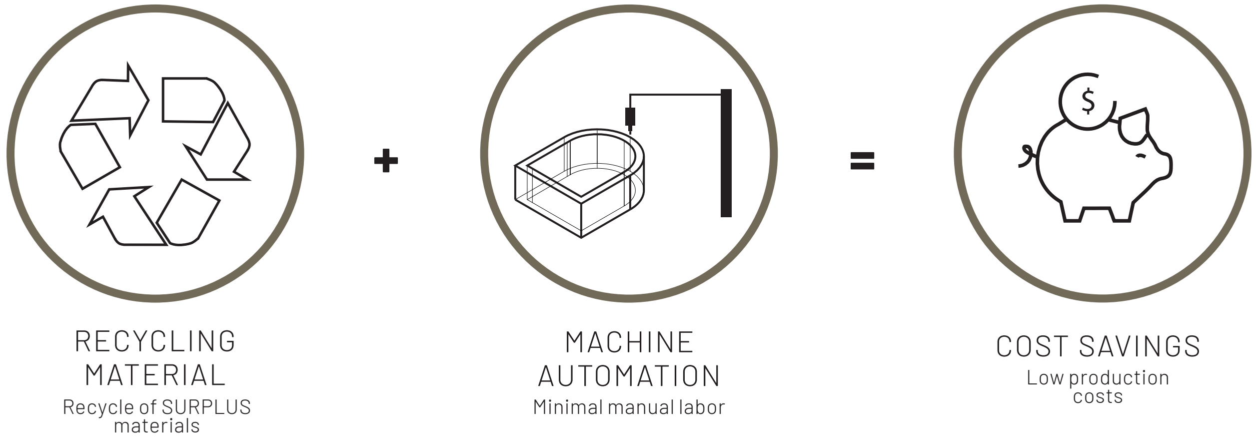


Figure:2.G
Utilization of recycled or surplus materials, implementation of automation, good acceible architecture.

RECYCLABILITY //

The concepts of reuse and recycling are frequently employed in discussions on sustainability, yet their precise meanings often remain ambiguous, complicating the interpretation of their underlying principles. With 3D printing using recycled materials, recyclability can be understood as a fully transformative process, whereby the materials undergo metamorphosis, allowing for their complete recovery and reintegration into new production cycles.

For example, once a printed structure fulfills its intended function, it can be deconstructed, processed into granules, and subsequently repurposed for new construction endeavors.In an era where resource scarcity is becoming increasingly prevalent, the recyclable nature of the material represents a strategic investment in the future of construction.

This approach challenges the traditional notion of permanence in building, suggesting that structures need not be static but can evolve in response to changing requirements. Thus, a building designed for permanence today can be seamlessly transitioned, through recycling, to meet the demands of tomorrow, embodying a dynamic and adaptable approach to architectural design and construction.

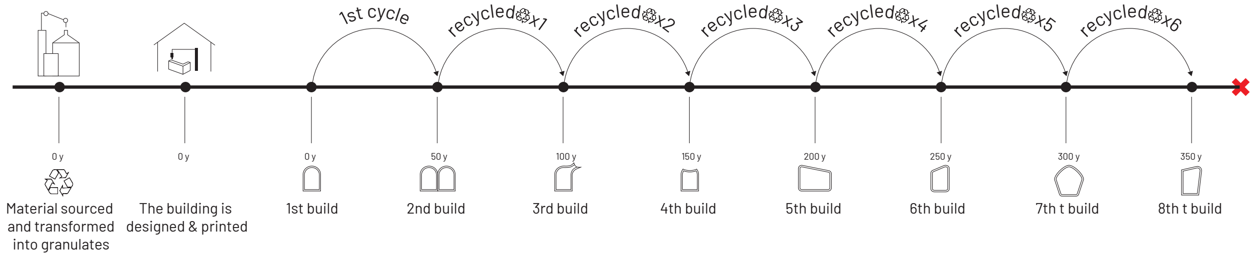


Figure:2.H
The lifespan of the material
Figure elaborated on page 31 (Figure:3.D)

WASTE MINIMIZATION //

Traditional construction practices are often characterized by the generation of considerable waste. In stark contrast, WOHN's 3D printing process significantly curtails such waste through its reliance on additive manufacturing (AM), which precisely utilizes only the material necessary for constructing the building structures.

This methodical approach to material usage inherently reduces waste production. Should waste materialize, this specific material methodology allows for its efficient recycling, transforming waste into granules that are reintegrated into the production cycle.

A distinct benefit of this 3D printing technology is its capacity to fabricate and then recycle its own moulds and prototypes. These components can be granulated and reused, epitomizing the waste minimization principle.This extent of waste minimisation opens opportunities to reconsider historically wasteful building types, such as temporary structures, as they can now be easily modified, repurposed, or reconstituted and reprinted.

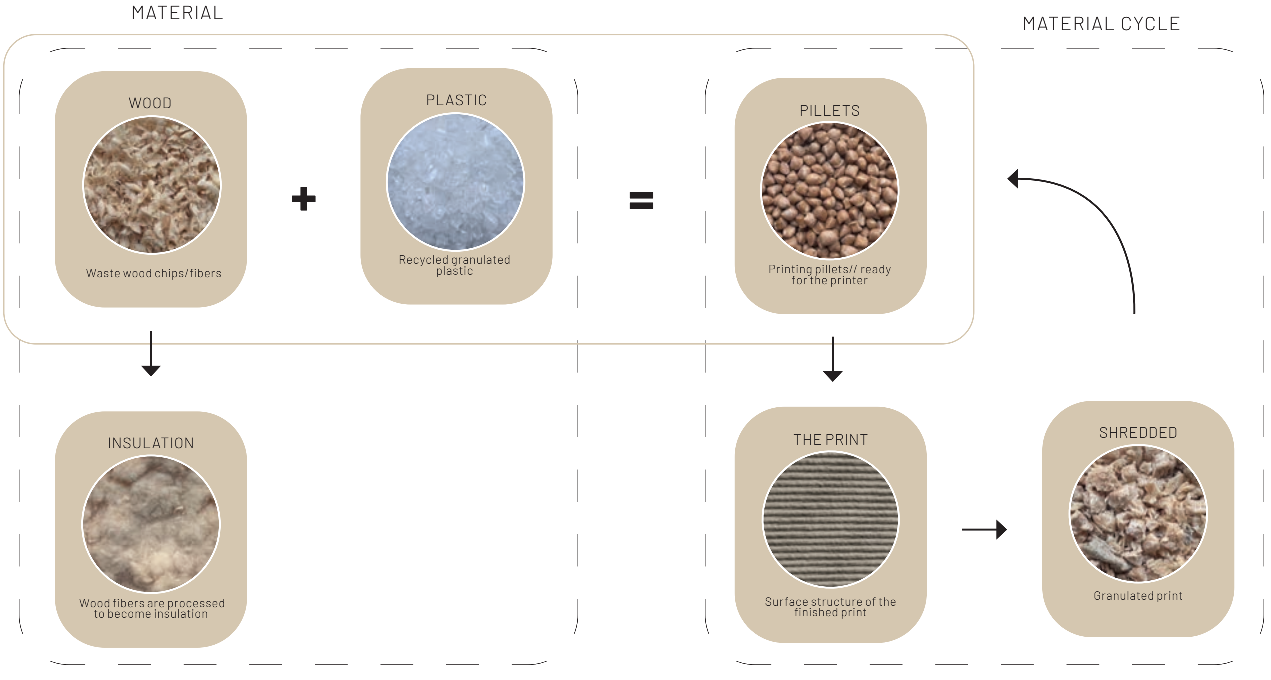


Figure:2.I
Mass production, high quality architecture
Figure elaborated on page 29 (Figure:3.A)

SUSTAINABILITY //

The after effects of the previous eight key characteristics of 3D printing is a move toward a more sustainable industry. We acknowledge that sustainability is a paradoxical term in architecture and construction given the extractive nature of material production throughout the manufacture and supply chain.

The combination of 3D printing and all the known advantages of custom production and waste minimisation that come with that technology are compounded here by the use of a fully recycled composite for the 3D printing that can in itself be recycled multiple times.

As a result, while the result may still arguably not be considered "sustainable" in an absolute sense, the widespread deployment of this technology will result in a radically reduced carbon output from the construction industry. If this radical reduction is to occur, we need to understand how to use the technology, maximising its opportunities and ameliorating or designing to accommodate its constraints. The full embrace of these possibillities results in a new aesthetic paradigm that can be compared in some ways to the advent of modernism as an aesthetic and spatial repsonse to the opportunities afforded by the new materials in the early 20th century.

OPGØR MED GREENWASHING

Forbrugerombudsmanden slår fast: Der findes ingen bæredygtige byggerier i Danmark

Man kan ikke definere, hvor lille et byggeris CO2-aftryk skal være, før man kan kalde det bæredygtigt, siger teknisk rådgiver for Forbrugerombudsmanden. Derfor er Reduction Roadmap heller ikke nok. Samtidig afviser instansen at lave et bæredygtighedsstempel i samarbejde med Rådet for Bæredygtigt Byggeri.

"THE CONSUMER OMBUDSMAN STATES: THERE ARE NO SUSTAINABLE CONSTRUCTIONS IN DENMARK.
ONE CANNOT DEFINE HOW SMALL A CONSTRUCTION'S CARBON FOOTPRINT SHOULD BE BEFORE CALLING IT SUSTAINABLE, SAYS THE TECHNICAL ADVISOR FOR THE CONSUMER OMBUDSMAN. THEREFORE, THE REDUCTION ROADMAP IS ALSO NOT SUFFICIENT. AT THE SAME TIME, THE AUTHORITY REFUSES TO CREATE A SUSTAINABILITY LABEL IN COLLABORATION WITH THE COUNCIL FOR SUSTAINABLE CONSTRUCTION."

Figure:2.J

Is sustainability even possible?

Picture: 2. a

PRINTING
Herlufmaugle

ZOOM: PLASTIC PAVILION
The seam where two surfaces meet

THE WOHN PRINTING PROCESS IN FOCUS

THIS SECTION EXPLORES THE SPECIFIC OPPORTUNITIES OF THE WOHN 3D PRINTING PROCESS IN DETAIL AND IN DOING SO, STARTS TO CLARIFY THE SPECIFIC AESTHETIC OPPORTUNITIES OF THE MATERIAL AND THE SYSTEM VIA WHICH IT IS REALISED.

PRINTING MATERIAL

Recycled wood fibres and biotech waste plastic presents a material foundation for circular 3D printing.

From waste to value. The material aims to reduce the carbon footprints in construction by utilizing waste wood fibers and biotech waste plastic from, among others, the pharmaceutical industry. Working towards developing a material that is not only sustainable in a 'reusable' sense but also addresses questions about strong, long-lasting constructions and extended life-cycles with its potential for transformation after the intended use.

The two input materials are blended together into a cohesive mass and are then refined into the pellets that the printer uses for printing (Figure:3.A).

WOOD //

One of the things that distinguish this material from others in the building industry is its ability to utilize very short wood fibers in loadbearing structures that otherwise would be burned as waste or used for then likes of mdf sheets, because they can not be used elswhere. Even with tiny fibres, the wood gives enourmous strength to the material composite used for printing.

The fibers initially resemble dust before being incorporated into the plastic mixture. Therefore, when sourcing large pieces of wood, the process is to first cut it into thin wood chips, then process it into short fibers, or collect it as sawdust for further processing.

Given that timber production is a subtractive process – where waste in the form of sawdust and cut-offs is inevitable, the material harness helps to lower the waste product of such processes. Various types of wood can be used, but pine and spruce are most common.

The raw wood fibers can also be used as insulating material. As some printed structures utilize a sandwich structure, the air pockets within the structure perfectly serve the purpose of providing space for insulation.

PLASTIC //

The plastic utilized in this process is derived from industrial and biotech plastic waste, with the objective of recycling the material and repurposing it.Polypropylene (PP), a thermoplastic polymer, emerges as the predominant material due to its extensive use in products in the meditech industry. These industries have high standards for cleanliness and hygiene which, for now, result in single-use plastics as the primary solutions to ensure sterile environments, thus producing a great amount of waste plastics. Its notable attributes include durability, chemical and heat resistance, and an advantageous low weight-to-strength ratio. PP's relative ease of printing, attributed to its low melting point.

THE COMPOSITE //

The composite material derives its advantages from the combined strength of wood fibers and the plasticity of the plastic. This fusion results in a material that is not only durable but also capable of multiple cycles of reuse. At the end of its lifecycle, the printed object can be dismantled, milled, shredded, ground up, and repurposed in new production cycles.

The presence of plastic in the material facilitates its melting and recycling, enabling the integration of "old" prints with new pellets for reuse in the 3D printing process.

TEXTURE, COLOUR & SIZE //

The print texture resembles layered or compressed cut wood, with bead tracks around 0.5 cm wide, imparting a striped and wavy texture for scale. Print sizes vary, but the dimensions of layers or bead tracks on the surface remain constant.

Upon contact, small wood particles adhere to the hand, akin to sawdust, enhancing the perception of a wooden material. In humid conditions, wood fibers cause the surface to absorb moisture, resulting in a cold, moist texture, with a scent reminiscent of wood or sawdust.

Prints usually have a golden color, shifting to more yellow hues over time. Pigments can be added during printing to alter the color or painted after hardening.

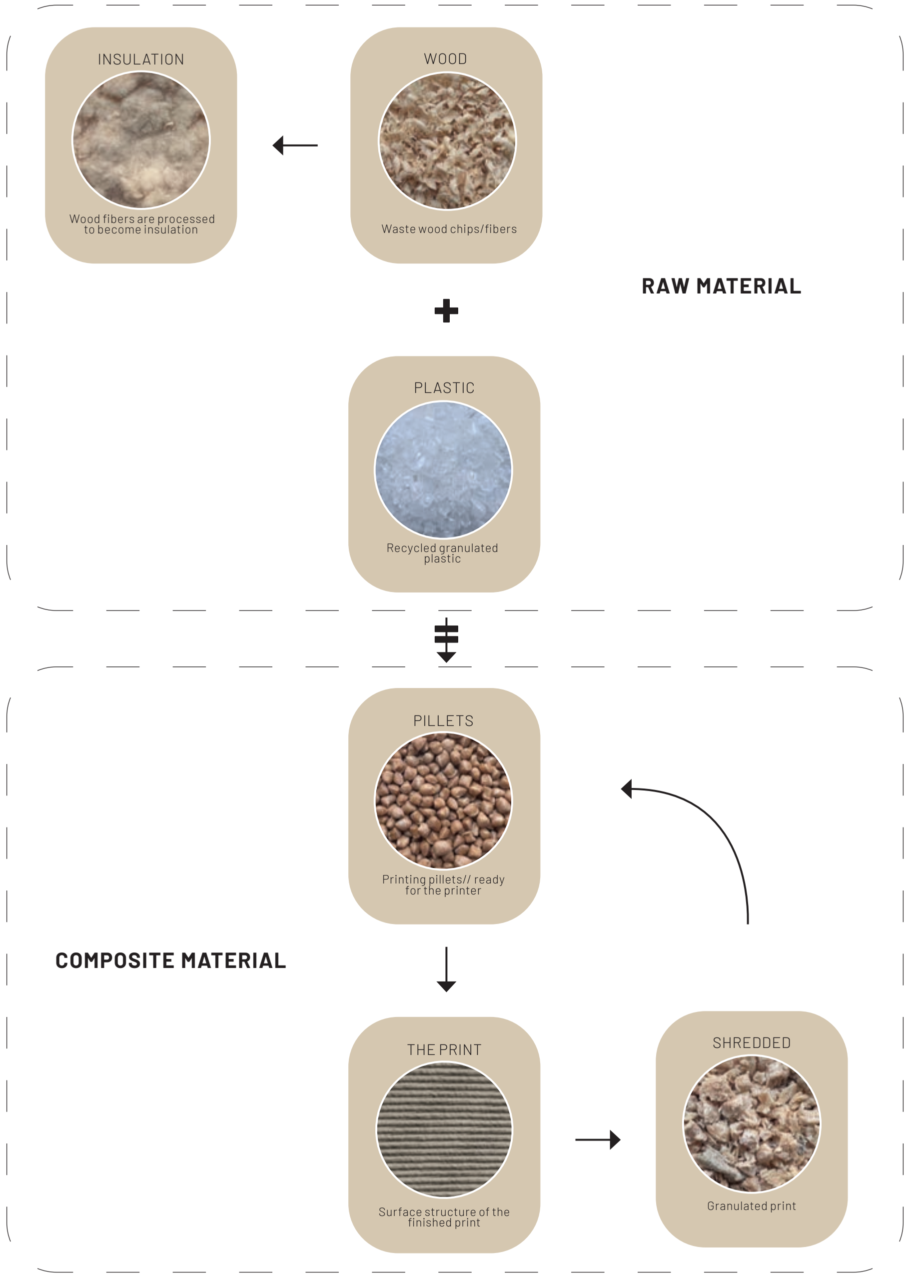


Figure:3.A
"Material morphology"
From waste to print

CIRCULARITY

This unique composite material offers a cyclical lifespan, allowing for repeating reprogramming, component adjustments and material alterations, enhancing sustainability and versatility.

The life cycles of materials and buildings are primarily assessed using Life Cycle Assessment (LCA) models. LCA models, a now well-understood methodology that is designed to evaluate the carbon emissions related to a particular material or suite of materials, and processes, over its life cycle. It enables professionals to determine critical parameters, including raw material extraction, manufacturing, transportation, construction, operation, and maintenance, as well as waste management and disposal of materials at the end of their lifespan, within the context of material sustainability[1].

The construction process typically unfolds as follows: Materials are extracted from natural sources, such as forests or mines. This raw matter is then refined, often through industrial processes that inevitably generate waste. During refinement, the raw matter is transformed into materials suitable for use in the construction industry. After this stage, the materials are utilized to construct buildings that have a lifespan typically ranging from 40 to 160 years, noting that most national building codes assume the lower end of this scale and buildings are constructed accordingly. (Figure:3.B)[5].

Although Life Cycle Assessment (LCA) suggests a cyclical process, it is often more linear in practice, as many materials lack feasible recycling options or are non-recyclable.

WOHN's approach to material life cycles and handling deviates significantly from traditional practices, encompassing all stages of construction—from design and installation to use and demolition.
With WOHN's technology and material composition, demolished and shredded materials at the end of a home's life can be directly reintegrated into new production lines (Figure:3.B). There is no distinction between shredded/reused and "new/raw" materials from other industries in terms of properties and quality, simplifying repurposing considerations.

The cyclical life process unfolds as follows: an architectural concept is designed and developed into a 3D model for printing, refined through test prints and prototypes. These prototypes can be shredded and reused for new prints when obsolete. After printing, post-processing may occur in the factory, including surface treatments or installations. The prefabricated building or components are then transported to the site for installation, where they serve their purpose until demolition. At this stage, the material is granulated/shredded and fed back into the production line for new designs. This cycle, potentially repeating up to seven times with each span lasting about 50 years, results in an overall lifecycle of 350 years (Figure:3.C).

A print may undergo numerous cycles, highlighting the potential for adaptability in meeting evolving programmatic needs through the straightforward addition or removal of building components. For instance, a change in the originally intended use, such as a family of four becoming a family of two, can precipitate new requirements (like the need for less space), necessitating revised spatial conditions. Equally, parts of a printed structure can be effortlessly removed, granulated, sold, and reintegrated into new production lines, or transformed into new, additional components.

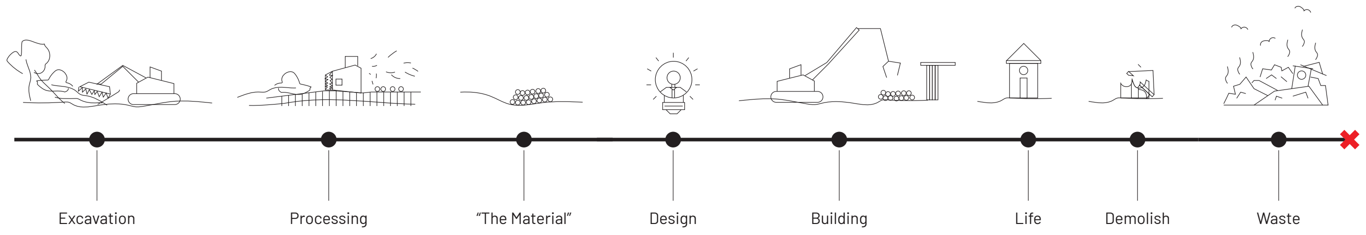


Figure:3.B

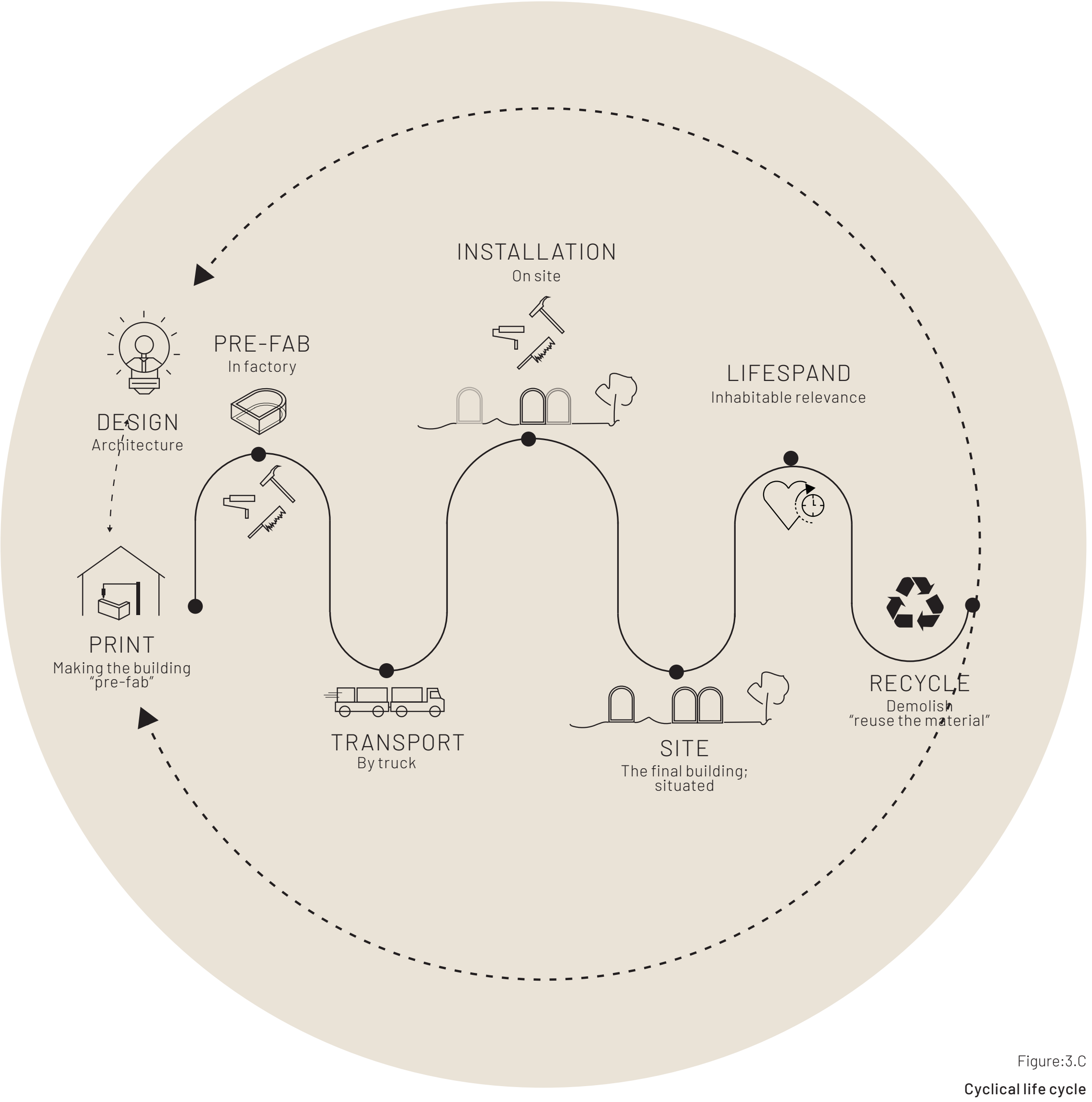


Figure:3.C

Cyclical life cycle
A true cyclical life

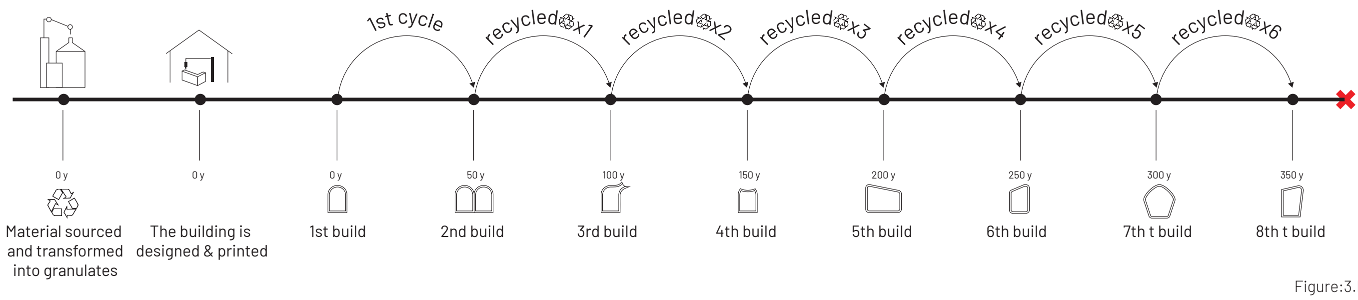


Figure:3.D

PRINTING PROCESS

Advanced 3D-technology creates the foundation for building with new perspectives, with the 3D-printer being one of the main actors.

3D-printing, also known as Additive Manufacturing (AM), is a process where three-dimensional objects are created by adding a material, layer by layer. This material fabrication method differs from traditional subtractive methods, where material is removed from a solid block, like wood or stone, to achieve the desired shape.

The objects are designed with the use of digital technology, resulting in a digital 3D model[2]. By providing the computer and 3D printer with the three-dimensional file, a physical (twin) object is reproduced, at a desired scale. While all 3D printers operate on this principle, they differ in various parameters such as pit size, printing material, morphological properties, and software compatibility, requiring a comprehensive understanding of the printer's specifications.

CONTEXT //

AM including 3D printing, is gradually gaining traction in the construction industry. The rationale for employing AM lies in its capability to fabricate complex geometries and customized designs without incurring additional costs. Moreover, it enables production with high precision and adaptability, without a significant increase in manual labor or material consumption.

While large building structures are being 3D printed globally, predominantly using concrete mixtures, this poses a challenge for AM's integration in the construction sector. Concrete's substantial carbon footprint exacerbates the industry's impact on climate change. Therefore, developing alternative materials that can replace concrete represents a significant opportunity. WOHN is at the forefront of this innovation, utilizing a material that is not only durable and robust but also has a minimal carbon footprint. This material is capable of being used to print extensive building structures, including load-bearing structures and houses.

LAYOUT OF THE PRINTER //

The 3D printing process can be delineated through five steps, as illustrated in (Figure:3.E). Initially, the pellets are stored in a dispenser that allocates them in precise quantities. Subsequently, the pellets are conveyed through an air dryer to eliminate moisture, preventing clustering and blockages in the feeding tubes. Once the optimal humidity level is achieved, a distribution pump propels the pellets towards the printer nozzle.

At the nozzle, the material is heated to the appropriate temperature, causing it to melt; concurrently, it is extruded through the nozzle. This phase is pivotal, as the interplay between the heating temperature and the material's properties determines the quality of the final output. Upon exiting the nozzle, the melted material is deposited onto a print plate where it solidifies, forming the desired shape.

MATERIAL FOR 3D PRINTING //

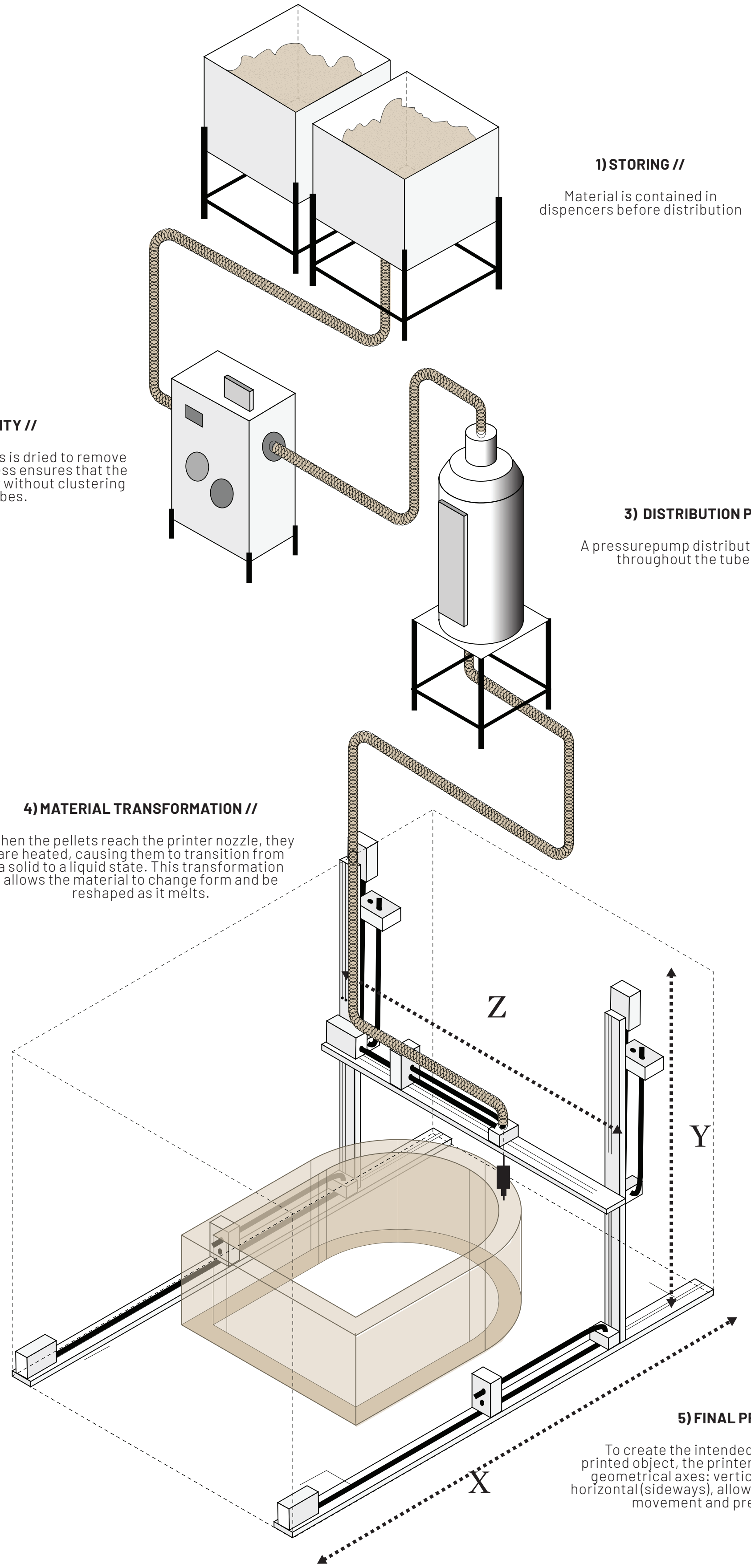
3D printing necessitates materials that align with the technological processes of the printer, be it Fused Deposition Modeling (FDM), Stereolithography (SLA), or Selective Laser Sintering (SLS). Regardless of the 3D printing technique, the materials require a high level of plasticity to facilitate extrusion through the nozzle. Consequently, thermal stability and heat resistance are imperative attributes, both during the printing process and within the final application environment.

SOLIDIFICATION AND LAYER TIME //

The interaction between material solidification time and printer speed is critical for determining print usability. Desynchronization between layer time and solidification time may result in issues like shrinkage, warping, or delamination.

Solidification time denotes the duration for print material to cure before the next layer. It varies; some require full solidification for layering success, while others benefit from partial molten layers.

Printer speed impacts layer time, determining the rate of extrusion for each layer in 3D printing. Higher speeds shorten printing time but may compromise quality, while slower speeds improve precision and smoothness, however extending print time and risking deposition on molten layers.



1) STORING //

Material is contained in dispencers before distribution

2) HUMIDITY //

All air around the pellets is dried to remove all moisture. This process ensures that the pellets can move freely without clustering in the tubes.

3) DISTRIBUTION PUMP //

A pressurepump distribute the material throughout the tube system.

4) MATERIAL TRANSFORMATION //

When the pellets reach the printer nozzle, they are heated, causing them to transition from a solid to a liquid state. This transformation allows the material to change form and be reshaped as it melts.

5) FINAL PRINT //

To create the intended shape of the final printed object, the printer operates along three geometrical axes: vertical (up and down) and horizontal (sideways), allowing for multidirectional movement and precise shaping.

Figure:3.E

THE WOHN PRINTING PROCESS IN FOCUS //

DIMINISHING HUMAN LABOUR //

A primary objective of 3D printing is to diminish human labor within the construction sector, thereby reducing costs and enabling the provision of affordable, accessible housing. To increase the efficiency of the construction process, WOHN emphasizes prefabrication in factory environments.

Conditions

In the WOHN factory, meticulously controlled conditions establish an ideal setting for construction activities, meeting material specifications, technical, mechanical, and human requirements, directly influencing the range of possibilities for management and processing.

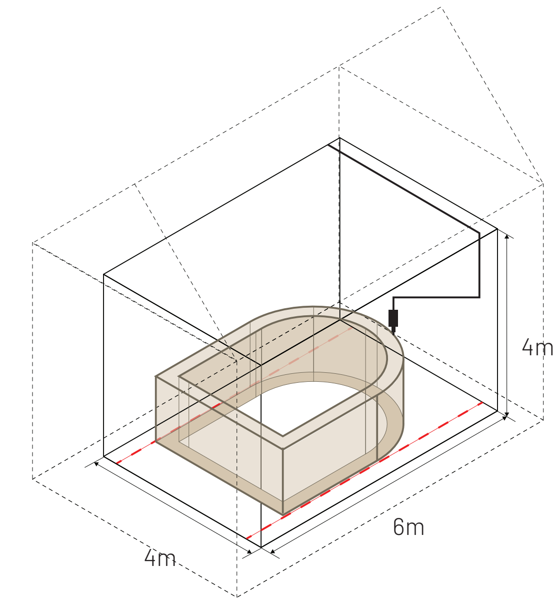
Print pit The printing operations are conducted locally at WOHN headquarters, where the printer setup includes a print pit measuring 4m x 4m x 6m. This size delineates the maximum dimensional potential to print within (Figure:3.F). However with the current material composite and morphology, and the specifications of the printer, a print that follows these dimentions is not possible to print.

Print size

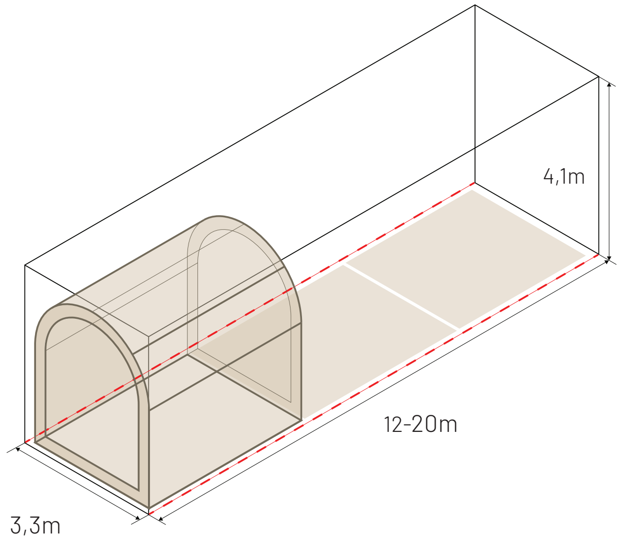
The printing size is governed by the complexity of the printed object. This complexity determines the speed of the printer. The more complex a shape, the smaller the print can be. This is because every time the printer needs to print small corners or turns, the speed must be reduced.

Transportation

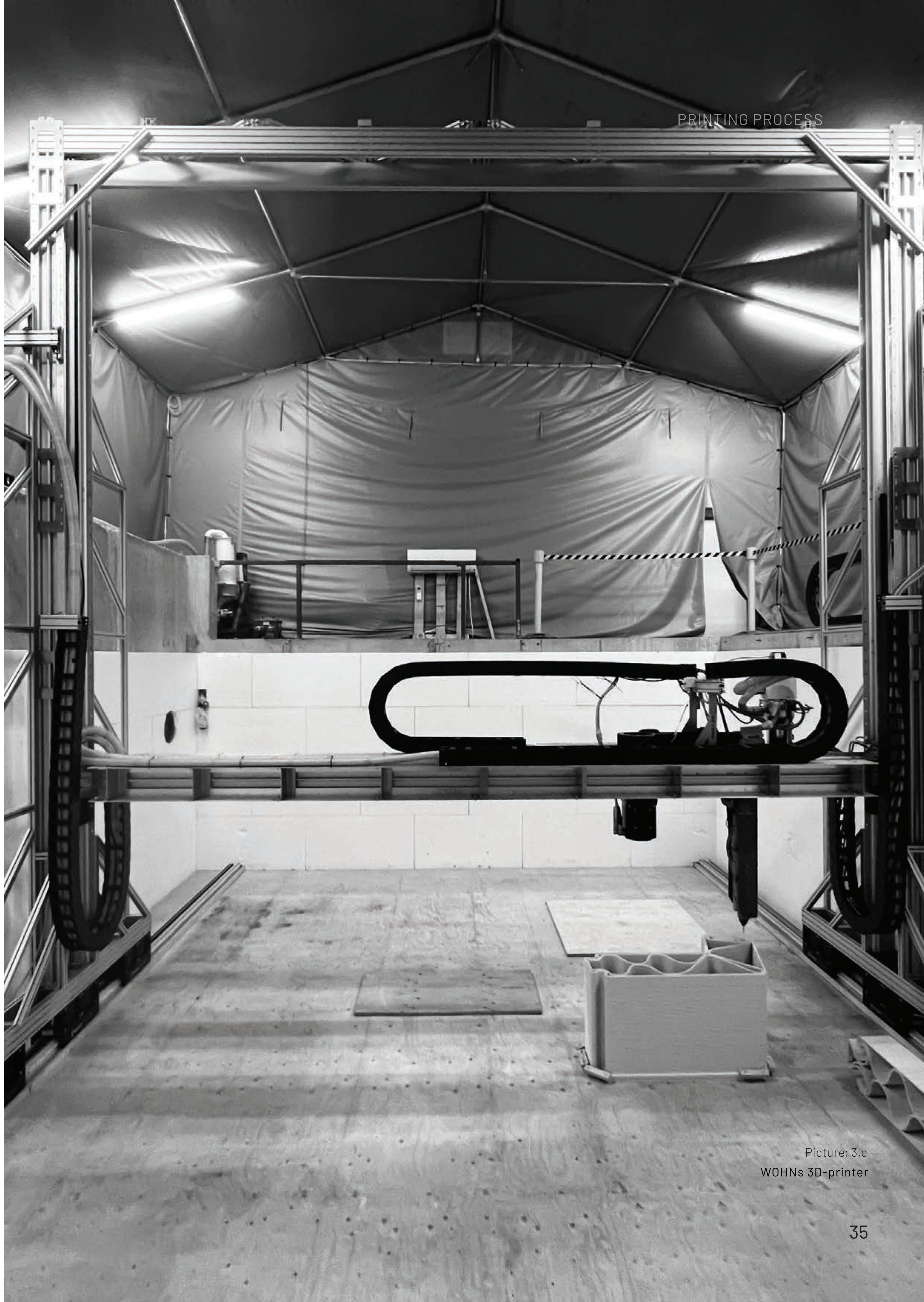
Wohn operates under two distinct strategies for on-site home installation: completing all construction and fabrication in the factory, subsequently transporting the entire print to the site for straightforward installation. The second strategy entails delivering prefabricated elements such as walls, roofs, and slabs to the site for easy assembly. In both cases, transportation is a critical factor, as the dimensions of standard trucks constrain the size of the prefabricated components, thereby influencing the design and scale of the prints (Figure:3.G).



Print pit
Printable area



Transportation
Truck measurements



Picture: 3.c
WOHNs 3D-printer

CONSTRUCTION TECHNIQUES

The construction techniques governing WOHN's 3D prints depend on the interplay between print direction, stresses, loading and the intended use of the structure.

The 3D printing process at WOHN is governed by an array of parameters that span material technical properties, printer capabilities, and handling features. These interconnected parameters collectively delineate the limitations and possibilities of the printing process.

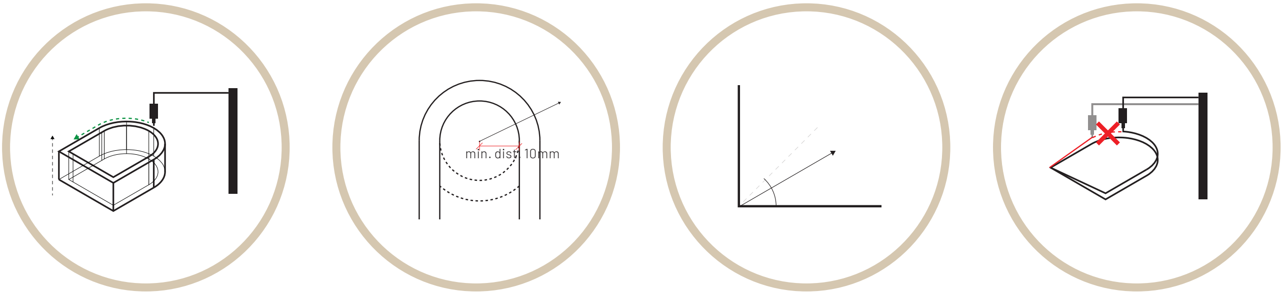
PRINTER SPECIFICATIONS //

The printer is equipped with a single screw extruder and a 3-axis gantry system, and has the capability to print at speeds up to 250 mm per second, using a nozzle diameter of 7mm. The interplay of the nozzle size and the material dispenser's pressure yields a bead dimension of 12mm in width and 3.2mm in height (Figure:3.J) & (Picture 3.b).

Prior to transforming a digital 3D model into a physical form using WOHN's 3D printing technology, it is essential to align key areas between the material's technical properties and the printer's capabilities.
These include: print direction, the turning ratio, eave and uninterrupted extrusion.

Picture: 3. f

COMPROMISED PRINT
Herlufmaugle



a) Loading direction

b) The turning ratio
1/2 bead width + bead width

c) Eaves (less than 30⁰)

d) Uninterrupted extrusion

Figure:3.H

LOADING DIRECTION //

The orientation of printing is crucial as loading[3] parrallel yields different benefits compared to loading perpendicular. The strength and durability of the print are affected by whether it is loaded parrallel or perpendicular, with respective decreases or increases in these properties. Additionally, the print direction has an impact on the spatial possibilities of the structure further details on the following pages.

DIRECTION & LOOPS //

It is imperative for the printing process to operate within a closed loop (Figure:3.I), avoiding any necessity for directional changes mid-print. Directional alterations can lead to printing over material that has not yet adequately solidified, particularly near the points of change, thereby compromising the stability and integrity of the print (Picture:3.f). Ensuring a continuous, unidirectional print path is crucial to maintain the structural integrity of the final product.

THE TURNING RATIO //

This parameter dictates the sharpness of edges that the printer can produce, affecting the design of corners in the printed object. The turning ratio is calculated based on the ratio between the "bead width" and a minimum distance of 10mm. Furthermore, the printing speed, and consequently the solidification time of the material, plays a vital role in defining the turning capabilities of the printer.

EAVE //

Refers to the overhanging section of the print, which is contingent upon the durability and performance of the printed material. Through comprehensive experimentation and analysis, WOHN has determined that their printer can achieve an overhang with angles up to 30 degrees. Overhangs pertain to the relationship between large and small bead path contact surfaces. The stability of the print diminishes as the contact surface between two print paths decreases. Optimal printing involves vertical progression with a consistent contact surface. While it is possible to reduce the contact area to create eaves, such modifications require precise pre-calculations to ensure structural stability.

UNINTERRUPTED EXTRUSION //

The distinct properties of WOHN's material, being heavier and less flexible than those utilized in smaller 3D printers, necessitate uninterrupted extrusion during printing. This characteristic limits the creation of openings or voids within a single print and precludes the simultaneous production of multiple objects.

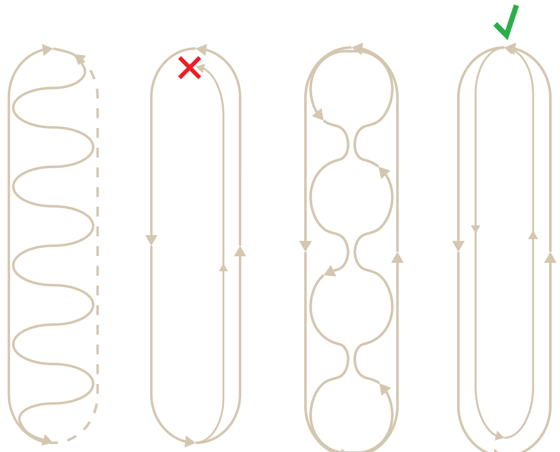
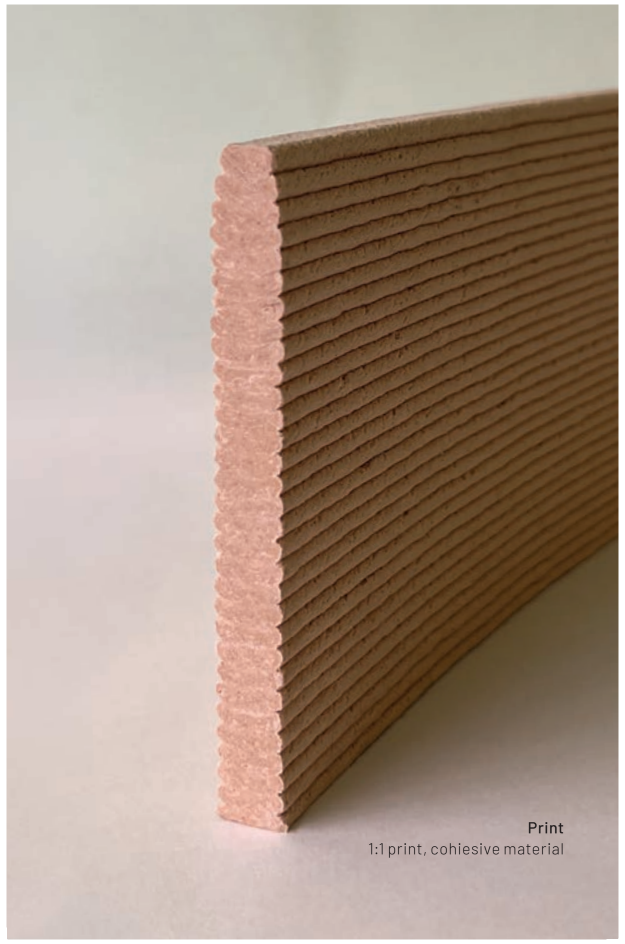


Figure:3.I

Not looping // PLAN
Would have to change direction

Loop // PLAN
Can print in the same direction



Print
1:1 print, cohesive material

CONSTRUCTION PARAMETERS

The construction techniques governing WOHN's 3D prints depend on the interplay between print direction, stresses, loading and the intended use of the structure.

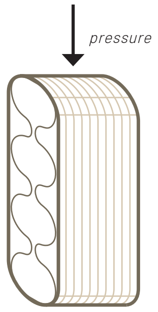
The construction tecniques for printing with WOHNs technology and materials are influenced by 3 overarching principles or "rules" which are necessary for the prints to be successful: The 3 principles regards: Print Direction and Looping, Tension and Compression, and Eave and Overhang.

Picture: 3. g

PLASTIC PAVILION
Thin layers

Figure:3.J

Applying presure againgt printing direction // ISO
Full stability and strenhg is obtained



Against printing direction // SECTIOON
Due to flixibility in the material it will not break

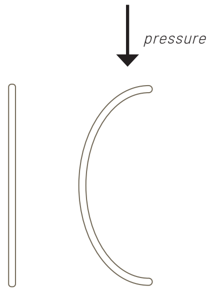
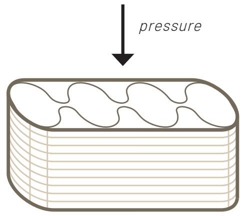
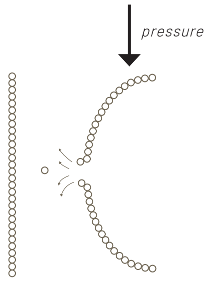


Figure:3.K

Applying presure in printing direction// ISO
Full stability and strenhg is lost



Printing direction // SECTION
Due to overlapping pint bead beeing the weakest part of the print, it can break



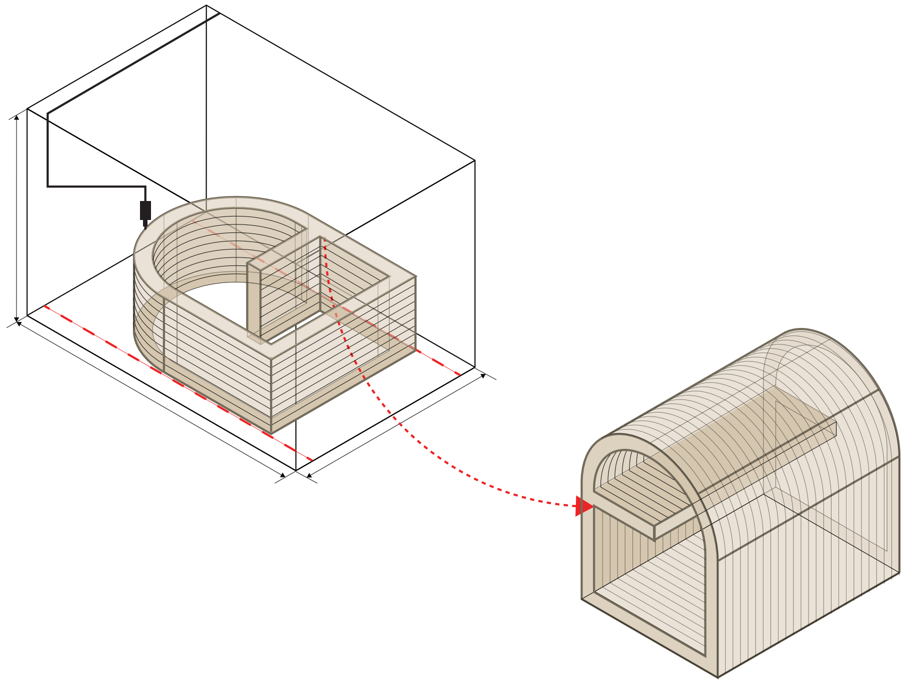


Figure:3.L

Loading direction
Loading normal (perpendicular) to the layers

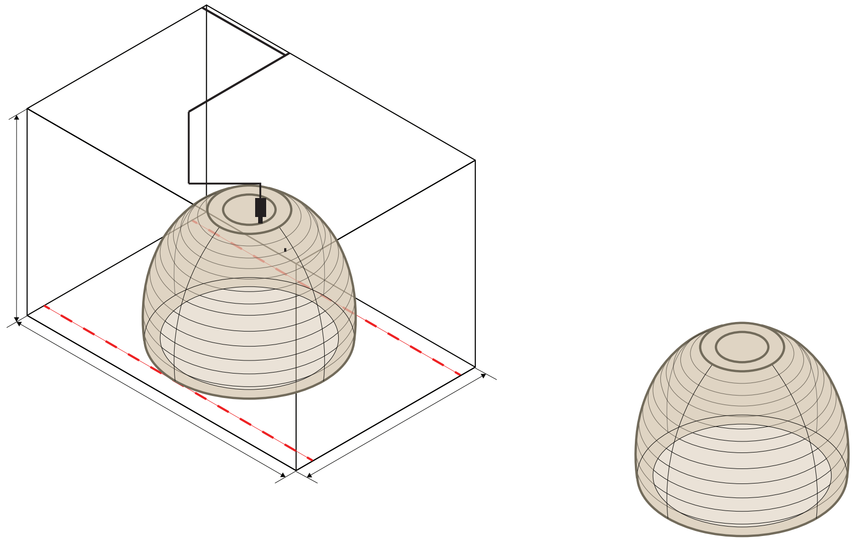
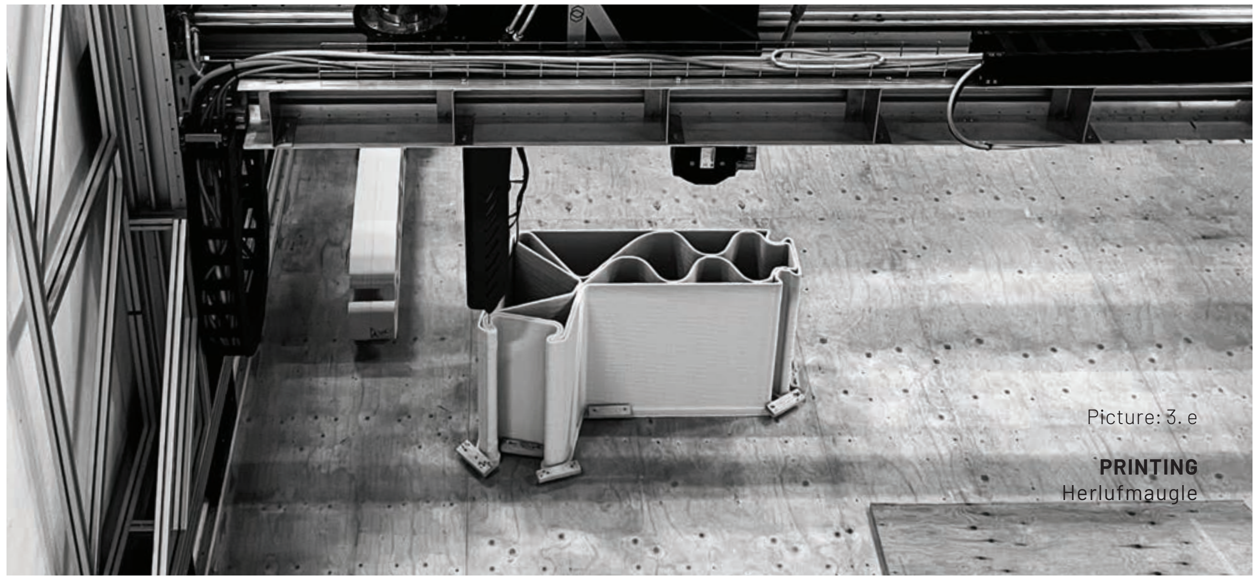


Figure:3.M

Loading direction
Loading parallel to the layers



Picture: 3. e

PRINTING
Herlufmaugle

SANDWICH STRUCTURES //

When WOHN undertakes printing parallel to the layers, the technique frequently used is to create a sandwich load-bearing structure, consisting of two outer face sheets (skins) and an inner core structure (Figure:3.O). WOHN's sandwich structures integrate the skins and the core into a unified entity through a single production process (Picture:3.e).

The advantage of these sandwich structures lies in their high stiffness, which is critical for WOHN due to the high strength yet relatively low stiffness of their materials. By orienting the weight forces along the print bead direction, increased stiffness is achieved (Figure:3.P). Moreover, this method ensures the material is used optimally, applied only where structurally needed (Figure:3.Q).

Employing a sandwich structure for printing when loading parrallel restricts the formal design options of the final print's plan diagram. These restrictions stem mainly from limitations related to eave and overhang (Figure:3.R) which in turn limit the printer's horizontal axis movements. Consequently, the architectural expression of 3D prints is typically characterized by linear extrusions in a single direction, indicative of these technical constraints.

Simultaneously, this approach facilitates high spatial variation in the sectional view, as the printer can move organically along the x and y-axis during the printing process (Figure:3.T).

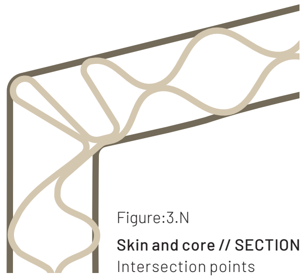


Figure:3.N

Skin and core // SECTION
Intersection points

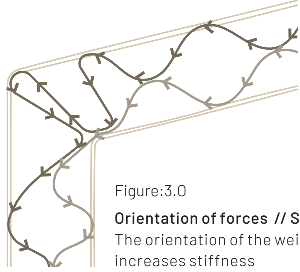


Figure:3.O

Orientation of forces // SECTION
The orientation of the weight forses, increases stiffness

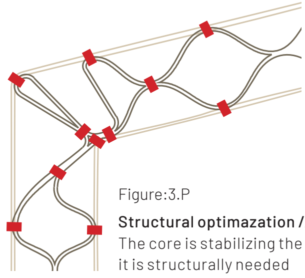


Figure:3.P

Structural optimazation // SECTION
The core is stabilizing the skins only where it is structurally needed

DOME AND CONE STRUCTURES //

The primary spatial advantages of loading perpendicular to the layers lies in the freedom to sculpt the plan arrangement as exemplified in (Figure:3.T) enabling designs that feature more organic and undulating spatial qualities. However, a notable drawback of this technique is its reduced strength, particularly for load-bearing structures with long ceiling and roof spans, compared to loading parallel to the layers.

To mitigate this, structural design principles resembling those in cone and dome structures must be employed to enhance the load-bearing capacity (Figure:3.S). The shape of these structures naturally diverts the gravitational forces, spreading them evenly across the surface and down to the ground (Figure:3.U), minimizing tensile stresses and making them exceptionally stable under their own weight and additional external loads.

Employing this printing method introduces a distinct formal and spatial repertoire compared to printing parallel to the layers. A significant advantage is the capacity to print thin surfaces or walls without the need for a bracing core, as otherwise seen in sandwich structures. This feature proves advantageous in scenarios where insulation is minimal or unnecessary, such as in stud walls, partition walls, or integrated furniture.

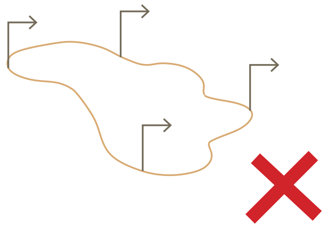


Figure:3.Q

Eave restrictions // ISO
The printer is restricted to printing curves on all axes due to eave limitations

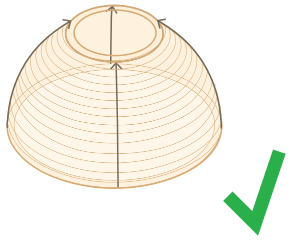


Figure:3.R

Self-loading // ISO
If the plan is regular, and the eave is less that 30^0, it is possible to print curves on all axes

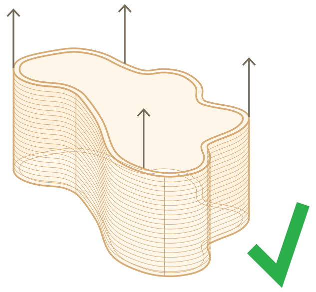


Figure:3.S

Curves in the plan // ISO
The core is stabilizing the skins only where it is structurally needed

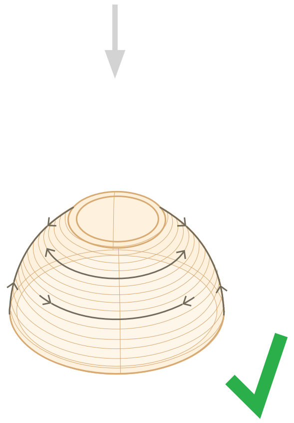


Figure:3.T

Stress diagram // ISO
If the plan is regular, and the eave is less that 30^0, it is possible to print curves on all axes

OPENINGS

Closed print circuit is essential when designing with the Wohn 3D printing system.

The design of 3D printed WOHN objects, whether they are entire buildings, building components, or smaller items from skin to furniture, necessitates an uninterrupted extrusion process, forming closed print circuits.

The constraints of eave and overhang, as discussed on the previous pages, influence the design of integrated openings like windows and doors within the print structure. Openings can be integrated into a design with a closed circuit in 4 ways:

1) TERMINATION OF PRINT //

During the printing process, irrespective of load direction, prints can conclude at varying layer heights, as shown in (Figure:3.V), allowing for integration of openings for windows and doors. This method accommodates standard rectangular frames but limits openings to the end of the print, consolidating them at one extremity in scenarios necessitating uninterrupted printing.

2) WITHIN THE PRINT //

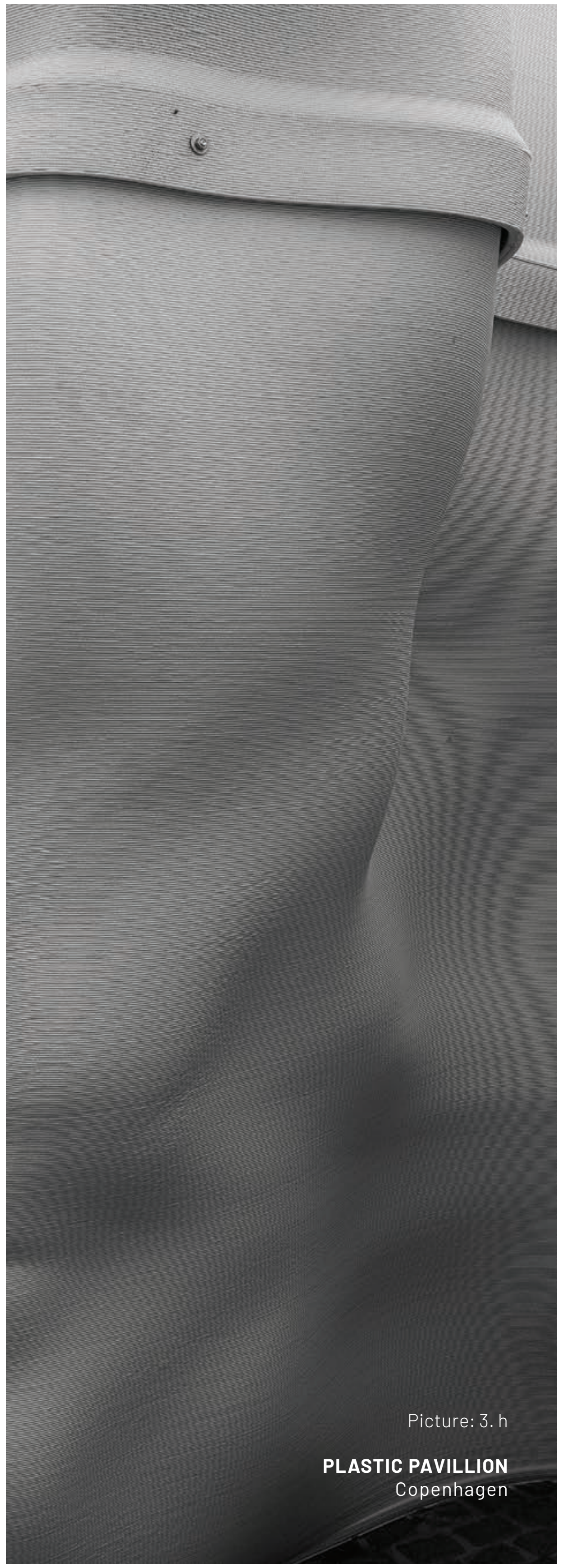
Openings situated within the structure, rather than at its extremity, must adhere to the 30-degree eave guideline. This stipulation leads to openings that tend to have an organic or diamond shape, positioned perpendicular to the direction of the layers. Consequently, these openings manifest distinct characteristics based on the direction of loading, as depicted in (Figure:3.W).

3) EXPOSED EDGES //

The next category of openings emerges naturally at the points where the printing ceases, revealing the structural edges. These openings, represented in (Figure:3.X), are the residual spaces left by the printing process at the structure's periphery.

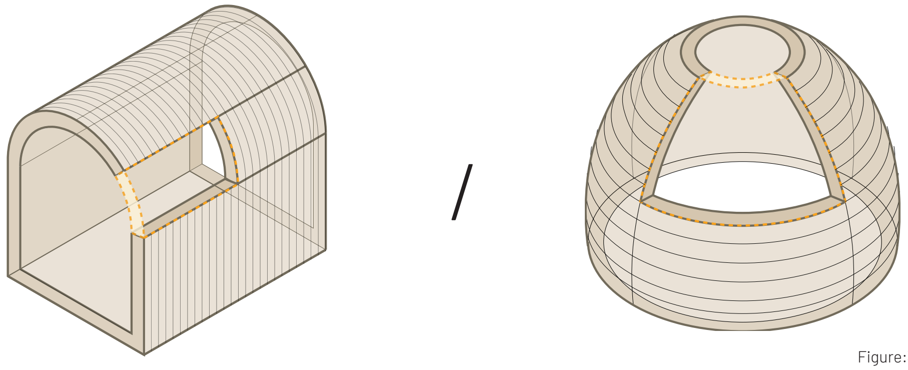
4) CUT OUTS //

A final alternative involves cutting out openings from an already completed print (Figure:3.Y). This approach is considered the least favorable due to the resultant excess material waste and as it leads to unnecessary energy consumption during printing.



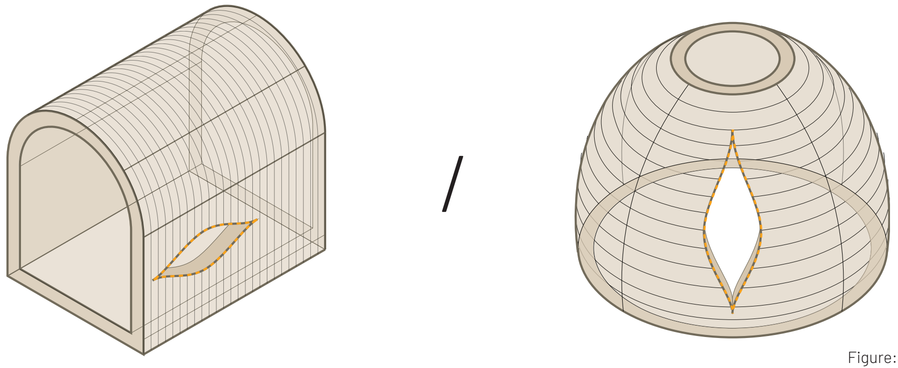
Picture: 3. h

PLASTIC PAVILLION
Copenhagen



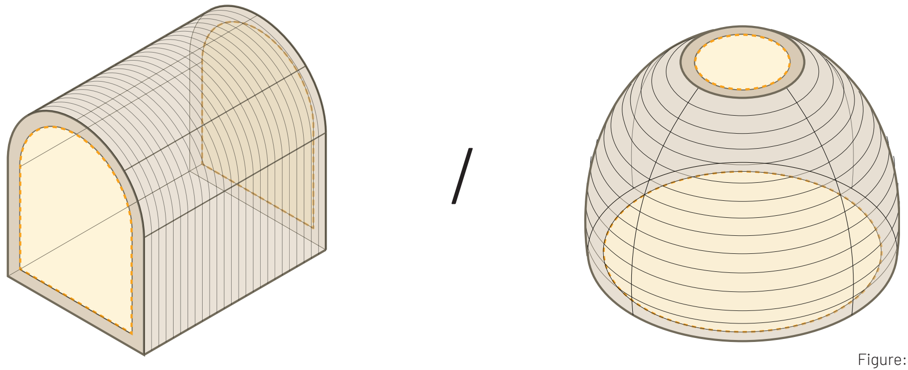
Termination of Print
Perpendicular loading

Figure:3.U
Termination of Print
Parallel loading



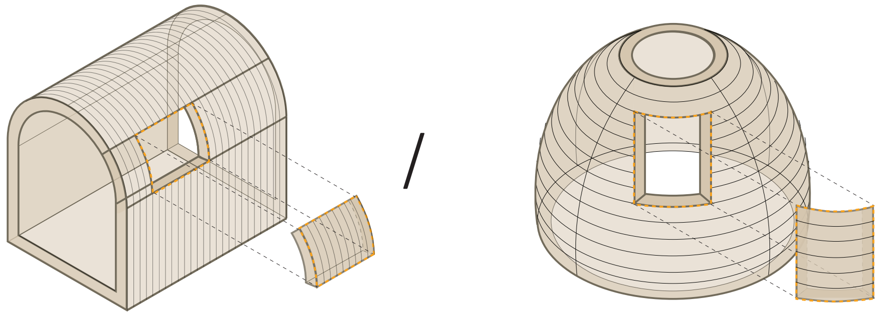
Within the Print
Perpendicular loading

Figure:3.V
Within the Print
Parallel loading



Exposed Edges
Perpendicular loading

Figure:3.W
Exposed Edges
Parallel loading



Cut outs
Perpendicular loading

Figure:3.X
Cut outs
Parallel loading

TECTONIC PROPERTIES

Regardless of whether the printing orientation is parallel or perpendicular to the layers, the construction methodologies exhibit four principal performative attributes:

LIGHTWEIGHT //

The structures are notably lightweight, facilitating ease of handling relative to conventional building systems. This characteristic primarily stems from the high optimization of the 3D printing process for structural efficacy, ensuring no excess material is produced. Material utilization is strategically focused on areas essential for force distribution and architectural requirements. Consequently, a WOHN 3D printed roof structure consumes considerably less material compared to traditional steel or concrete structures, where material distribution cannot be as precisely controlled.

LOAD BEARING //

While printing parallel or perpendicular to the layers results in distinct scenarios for managing bending and tension forces, both orientations can facilitate load-bearing structures. The material's ability to function as a load-bearing element is crucial within the construction industry, where handling such forces represents a significant challenge, particularly in the shift towards sustainability. Loadbearing structures significantly impact a building's CO2 footprint, underscoring the importance of addressing this aspect for environmental sustainability.

INTEGRATED FITTINGS //

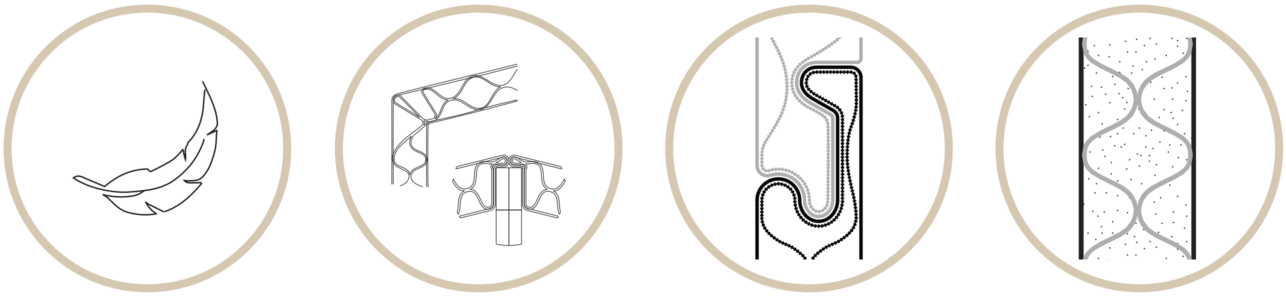
Fittings and joinery, the critical elements that connect various building components, often constitute a significant portion of the total material mass in construction, yet they frequently go unnoticed. These junctions, where components intersect, typically form the most vulnerable points of a structure.

Leveraging the high precision of 3D printing and the logic of additive manufacturing, along with specific material properties, it is feasible by design to incorporat fittings and joinery directly into the building structures (Picture 3.j). This approach is akin to an enlarged Lego system, where additional materials are unnecessary for joining the elements, thus streamlining construction and enhancing structural integrity.

INHERENT SPACE FOR INSULATION //

Designing the load-bearing structure as a sandwich inherently creates spaces for insulation within. This configuration facilitates the incorporation of insulation materials in a factory setting prior to on-site installation, streamlining both the fabrication and erection processes. Such an approach not only simplifies construction but also enhances affordability by integrating essential insulation spaces directly into the structural design, negating the need for additional adjustments or modifications during the building phase (Figure:3.M).

In crafting a unified skin and core construction within a single entity, the structure gains attributes like lightness and stability, coupled with the formation of air pockets. These air pockets interspersed throughout the structure create cavities that offer insulation, playing a crucial role in the regulation of temperature and acoustics (Figure:3.M).



a) Light weight

b) Load bearing

c) Integrated fittings

d) Insulation

Figure:3.Y

Picture : 3.j

JOINTS AND MEETINGS
Herflumagle

TRANSITIONS AND JUNCTIONS

Analyzing transitions and junctions between architectural elements is essential for discerning their potential to influence design.

These intersection points offer significant aesthetic and functional opportunities, as shown in (Picture:4.i), shaping a building's spatial experience, aesthetic integrity, and structural soundness. Transitional design requires rigorous inquiry into a building's dynamic interaction with its environment, examining the interrelation between the biosphere (context) and technosphere (building). Integrating interior elements like merging furniture with walls or blending vertical and horizontal planes is paramount. This prompts a reevaluation of traditional architectural classifications, advocating for an integrated and responsive approach that aligns architectural expression with functional needs and environmental congruity.

INTERPLAY OF SKINS, CORE, AND INSULATION //

The interrelationships between the exterior and interior skins, core structure, and insulation (Figure:3.AA) plays a vital role for the spatial and functional properties of the 3D print. Different components can interact within the structure, offering opportunities to innovate in thermal performance, aesthetic expression, and structural efficiency (these questions are examined later in the reprt).

PRINT AND SPACE RELATIONSHIP //

Evaluating the relationship between the structural/ print dimensions and the spatial context, facilitates the creation of environmentally responsive designs with precise specificity. This necessitates a comprehensive examination of how the physical form and construction methodology impact and shape the spatial character and functionality of a building.

Such an analysis requires rethinking traditional spatial concepts through the lens of advanced technological capabilities such as how to integrate natural light into a building (Figure:3.AB) or how to spatially organize movement in relation to internal objects (Figure:3.AC). This underscores the potential of 3D printing to redefine spaces, making them more adaptive and responsive to both their physical and functional environments.

Picture: 3. i

INTERSECTING
Herlufmaugle

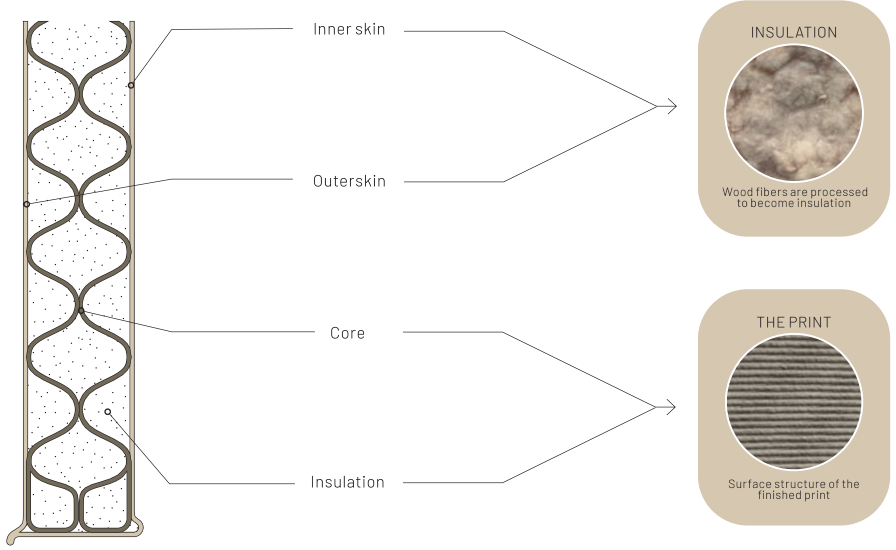


Figure:3.Z
Interrelationships

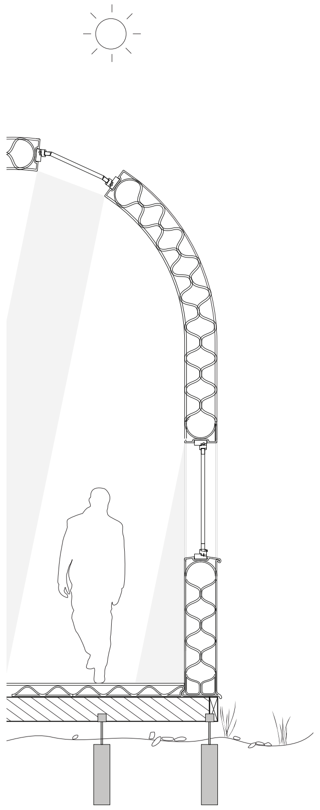


Figure:3.AA
Integration of natural light

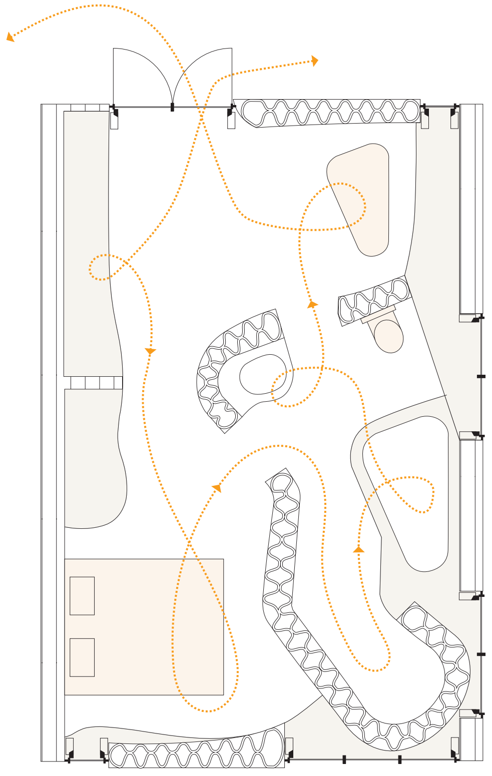


Figure:3.AB
Spatial organization

ZOOM; PLASTIC PAVILION
The seam where two surfaces meet

FORMAL AND SPATIAL PROPOSITIONS

THE SUBSEQUENT SECTIONS EXPLORE QUESTIONS RELATED TO ARCHITECTURAL DESIGN AND COMPOSITION. IT DELVES INTO THE IMPLICATIONS OF LOADING CONFIGURATIONS—PARALLEL VERSUS PERPENDICULAR. COHESIVE DESIGN STRATEGY THEN EXAMINES VARIOUS PROPERTIES TO MAXIMIZE THE POTENTIAL OF 3D PRINTING IN ARCHITECTURAL APPLICATIONS.

SIMPLE VS COMPLEX CONSTRUCTIONS

In the context of 3D printed structures, it is feasible to operate within a spectrum ranging from simple to complex constructions.

When designing building constructions and spaces, two primary methods are typically utilized, referred to for clarity as simple and complex constructions.

SIMPLE CONSTRUCTIONS //

Simple constructions adopt a design philosophy wherein, ideally, all components are fabricated as a single, cohesive unit, thereby eliminating the need for additional fittings or joinery. This approach aims to achieve a monocoque structure, where the entirety of the form serves as both the exterior and the load-bearing system. Practically, this could also involve printing elements with integrated or pre-designed joints and fittings, as depicted in (Figure:4.A). Such a method significantly reduces assembly and handling costs since manual labor is minimized by producing the structure in one comprehensive process.

COMPLEX CONSTRUCTIONS //

Conversely, complex constructions entail a design strategy where each building component is crafted and assembled separately. This method is prevalent in most modern construction practices and capitalizes on specialization.

This method facilitates a higher degree of spatial and formal diversity, both within individual elements and in their interrelations as components, thereby contributing to a more complex overall composition.

Each element is individually manufactured, often on a mass scale, to reduce production costs. However, while production expenses may be lower, the complexity and diversity of the components typically lead to higher costs in handling and assembly. The intricate process of integrating various elements necessitates meticulous coordination and can escalate overall construction expenses due to the intricate fitting requirements of numerous disparate parts (Figure:4.B).

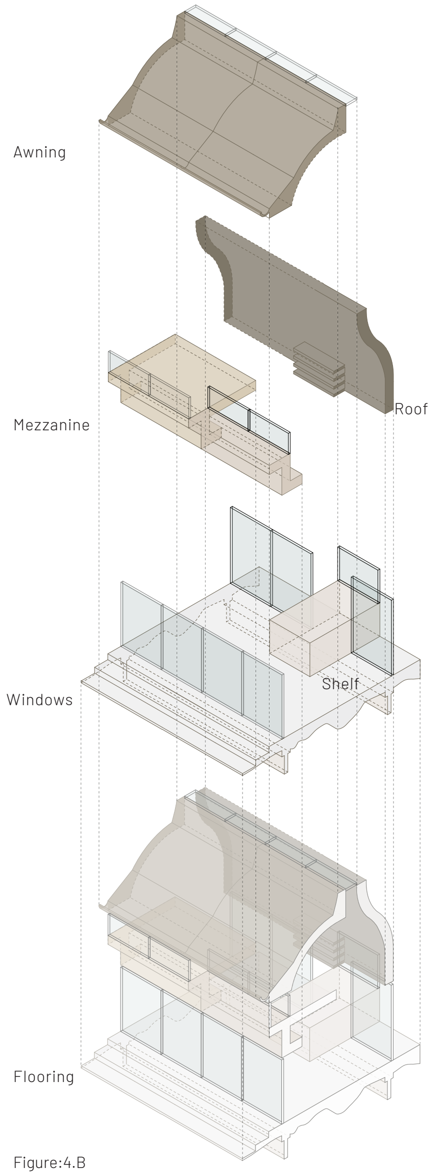


Figure:4.B
Elemenal/modular structures
Multible prints

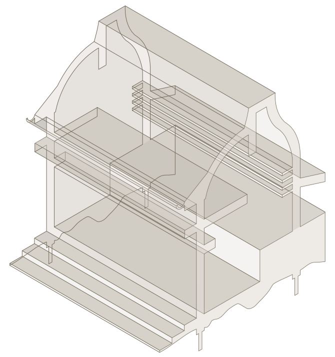
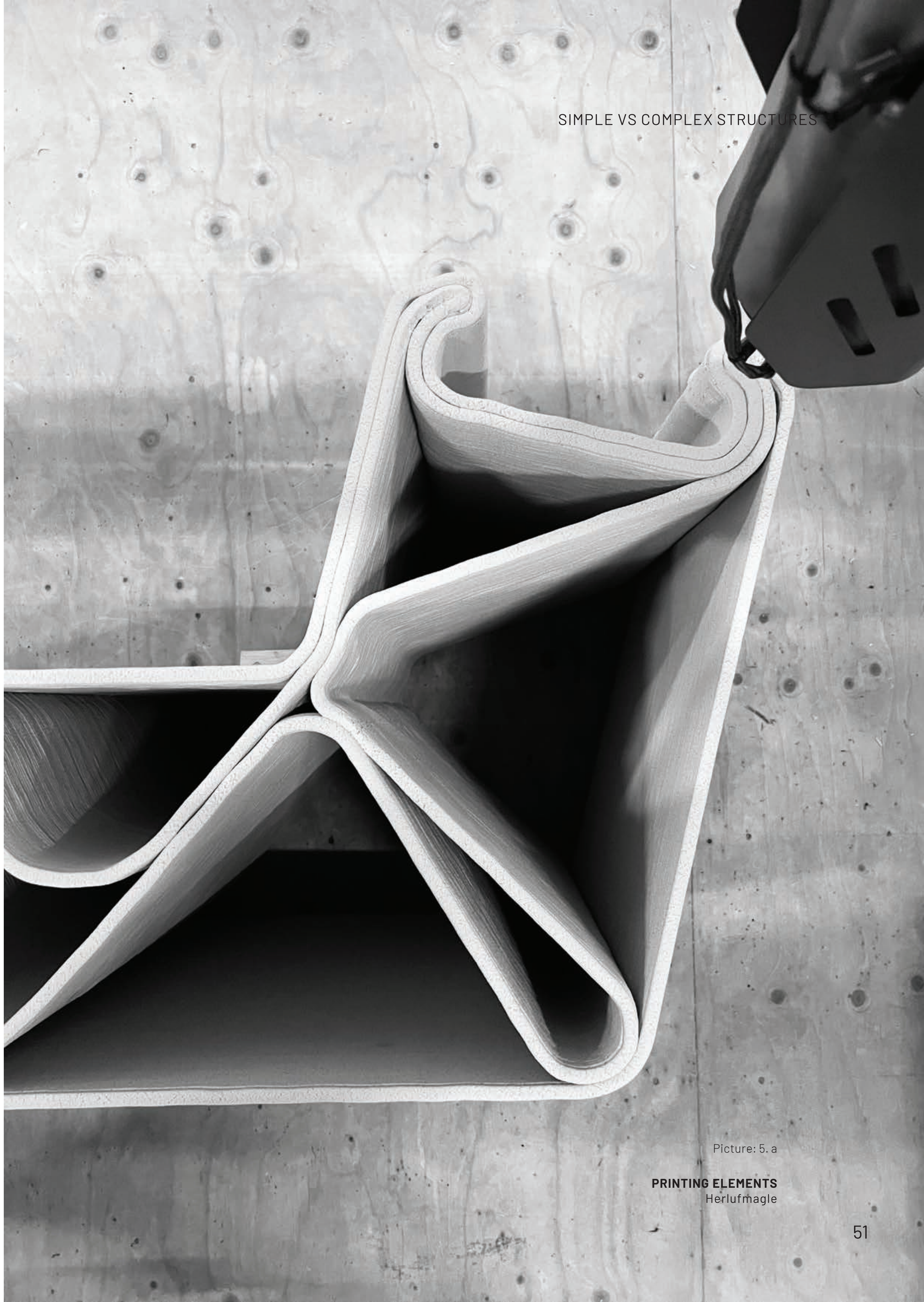


Figure:4.A
Monocoque structure
One print



Picture: 5. a

PRINTING ELEMENTS
Herlufmagle

LOADING PARALLEL

Loading parallel allows great flexibility in enabling the printing of loadbearing elements designed in sectional elements as part of a larger structure that can, theoretically at least, be infinitely large and not constrained by the print pit and technical issues.

When applying loads parallel to the printing layers (refer to page 44) and utilizing a sandwich structure, there are specific implications for the design of each key building component: the base stucture, interior, exterior, and combinations of all three. Looking across these methodologies not only challenge conventional construction paradigms but also open up innovative avenues for architectural expression and functionality.

BASE STRUCTURE

The foundational approach to designing with the sandwich structure involves aligning the skins parallelly from the interior to the exterior.

While not fully leveraging 3D printing's capabilities, this method creates familiar spaces, bridging traditional construction with innovative 3D printing possibilities. As discussed earlier, the sandwich structure serves as the core load-bearing principle for this construction technique, a pivotal design parameter.

INTERIOR

From an interior design perspective, the discourse includes integrating the building's structure with its internal spatial arrangements, reliefs, furniture, and installations. The 3D printer's capability to indiscriminately produce curved walls, shelves, overhangs, slabs, and flat surfaces enables the fusion of these various typologies into cohesive, singular solutions within the house's design.

This integration streamlines construction processes and unveils new spatial possibilities akin to the compact, multifunctional, and aesthetically unified environments found in boat or ship cabin designs. In these settings, functionality, space utilization, and aesthetics converge seamlessly.

The foundational principle when questioning the interior design is a consequence of the sandwich structure involving configuration where the exterior and interior skins are reinforced by an internal core as shown previously (Figure:3.AA). Modifying the interior implies that the inner skin no longer aligns parallel to the exterior skin, leading to the emergence of novel spatial formations.

Irrespective of specific functions and interior typologies, a principal characteristic is observed in the spatial composition and negotiation, particularly in the deviation and interaction around the line or curvature of the original base interior skin (Figure:4.C).

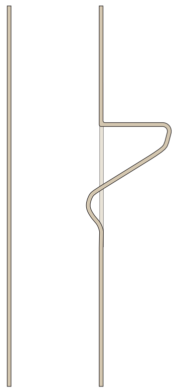
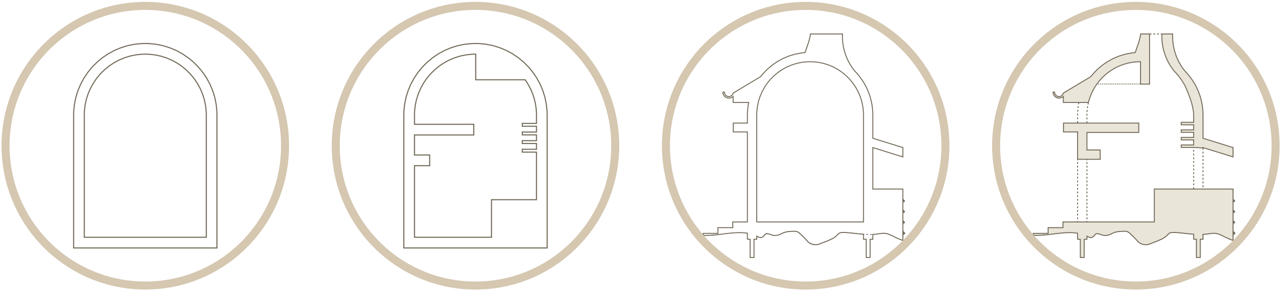


Figure:4.C



a) Base Structure

b) Interoir

c) Exteroir

d) Combination

Figure:4.D

Modifying this line to delineate around the baseline, thereby introducing new dimensions of depth and dynamism, unveils a range of design possibilities. A practical manifestation of this principle is the integration or sculpting of shelving systems or storage space for installations directly into the wall structures space, as illustrated in (Figure:4.E) & (Figure:4.F).

Alternatively, as a contrasting approach, the interior wall's skin might be extruded or projected into the room, creating physical and visual depth becoming various functions such as shelves, furnitures or mezzanines as shown in (Figure:4.H) & (Figure:4.I) & (Figure:4.J) & (Figure:4.K).

When shelves, furniture or other spatial elements are designed as part of the walls, a spatial interplay begins between the interior skin and the wall's core, as examplified in (Figure:4.G). This interaction may be subtle or overtly articulated, potentially influencing both the interior and exterior appearances, resulting in formal variations as observed in (Figure:4.G).

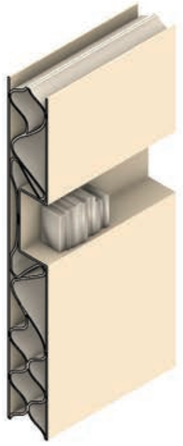
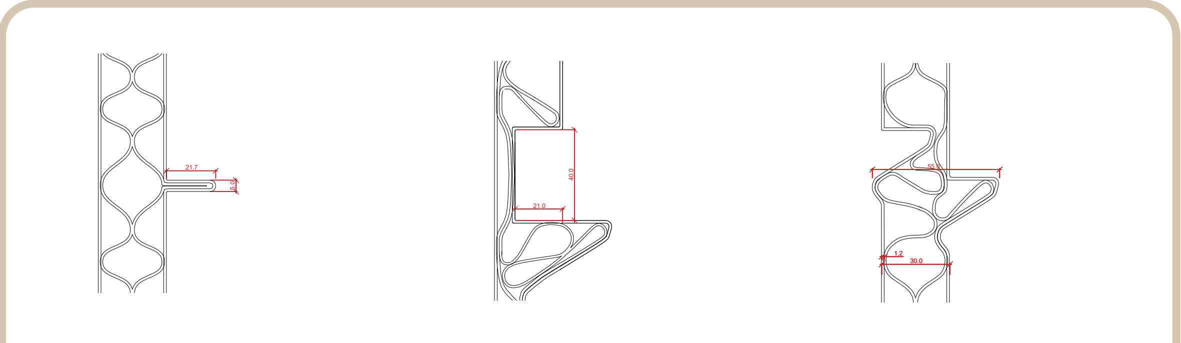


Figure:4.E
Shelf integrated in main print
Parallel loading

Figure:4.F
Installation integrated and hidden
Parallel loading

Figure:4.G



Simple shelf
Parallel loading

Shelf with overhang
Parallel loading

Shelf exterior and interior reacts
Parallel loading

Figure:4.H
Reactive inner and outer skin
Parallel loading

Figure:4.I
Bench integrated in main print
Parallel loading

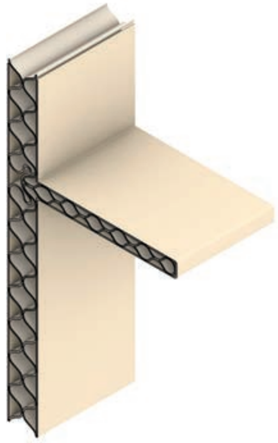


Figure:4.J
Mezzanine integrated in main print
Parallel loading

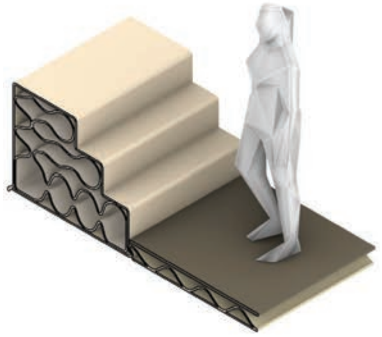


Figure:4.K
Steps integrated in mail print
Parallel loading

LOADING PARALLEL

Picture : 4.c

ZOOM; PLASTIC PAVILION
The seam where two surfaces meet

EXTERIOR //

Reflecting the adaptability found in interior design, the exterior of a 3D-printed WOHN structure similarly exhibits considerable flexibility. Many of the considerations pertinent to interior design also translate to the exterior realm, such as integrated furniture, shelving, and staircases as discussed and shown in (Figure:4.H) & (Figure:4.I) & (Figure:4.J) & (Figure:4.K).

Viewing the design from an exterior perspective emphasizes the interplay between the building and its surroundings. Key questions arise about how the building spatially responds to its environment (biosphere, light, wind, temperature etc) and the formal and spatial ramifications of this interaction on the 3D-printed structure (Figure:4.L).

Foundationing and Integration with the ground

The capability of 3D printing to facilitate a virtually unrestricted formative language, coupled with a relatively lightweight structural system, offers diverse scenarios for how buildings interact with the ground.

For example, structures could be designed to "float", supported by chassis and helical piles (Figure:4.M), where elements such as stairs or outdoor furniture delineate the transitions between the building and the terrain (Figure:4.N). Alternatively, buildings that conform to the existing landscape with the same level of precision and freedom as captured by 3D scanning technology are possible.

Figure:4.L
Water drainage/eave
Parallel loading

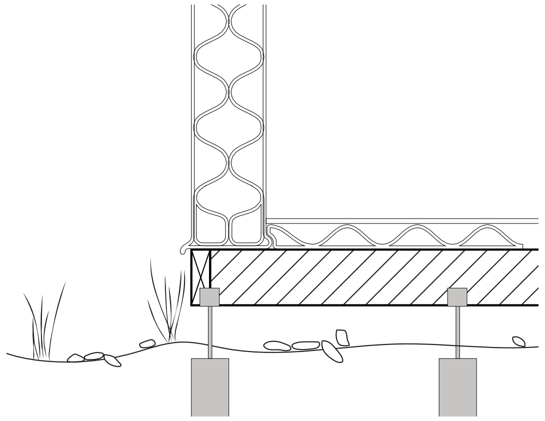


Figure:4.M
Foundation, helical piles
Stability and strenhg is obtained

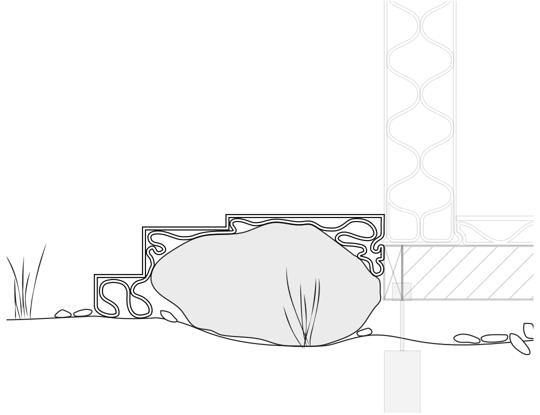


Figure:4.N
Staircase adapted to context
Stability and strenhg is obtained

Design details

Cantilevers, canopies, dormers, zeniths, and chimneys are architectural elements that extend from the main structure of a building, engaging with its surroundings to create spaces and niches both beneath and around the building's exterior, as illustrated in (Figure:4.P).

These details, when seamlessly integrated into the building's 3D printed structure, unveil innovative approaches to shaping and defining zones of interaction between the building and its environment.

Emerging smoothly from the building's surface, these elements embody the functional and sensory extensions of the structure, akin to the eyes, ears, arms, and legs of a living organism. They transform the building from a mere container into a dynamic entity, imbuing it with character and vitality through movements and rhythms that resonate with the environmental context and location.

Water management

Among some of the exterior aspects that introduce design questions is how the building's skin can be designed to manage water, either by incorporating gutters into the overall structure, as shown in (Figure:4.O), or built after protrusions and/or setbacks that directs rain water to specifc places (Figure:4.L).

These elements can be seamlessly integrated, forming almost invisible channels that align with the core structure's logic, as depicted in (Figure:4.O). Or, gutters can serve as decorative elements, accentuating the transition from the facade to the roof structure, illustrated in (Figure:4.R).

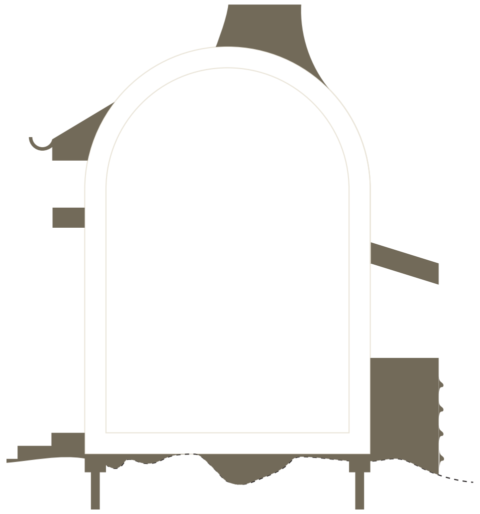


Figure:4.P
Engaging with surroundings
Parallel loading

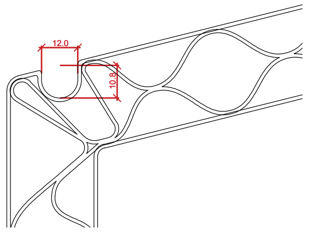


Figure:4.O
Gutter, integrated,invisible
Parallel loading

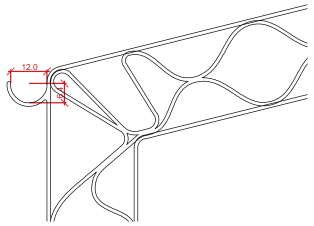


Figure:4.Q
Gutter, exterior
Parallel loading

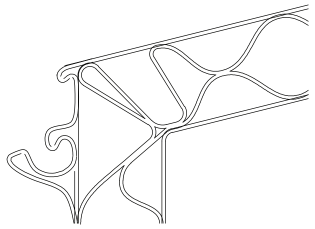


Figure:4.R
Gutter, integrated, decorative
Parallel loading

COMBINATIONS AND INTERFACES //

The design process that considers the interplay between interior and exterior elements evolves into a dynamic exchange of actions and responses. The interior and exterior skins, with the core acting as a mediating element, dynamically influence each other's configurations.

A process of spatial and formal sculpting becomes feasible through the 3D printer's capability to seamlessly integrate different elements, leveraging the material's plasticity and moldability. The design methodology thus embodies a continuous iterative process of addition and subtraction, expansion and contraction, engagement and retraction. It represents a dialogue between scales, encapsulated within a singular design continuum, akin to a pencil whose line continuously flows across the paper without interruption.

An interior shelve detail might mimic an exterior facade rhythm (Figure:4.S). Or an exterior gutter might define the transition between facade and roof ridge, leading to the relationship between window and mezzanine becomes a spatially defining moment both inside and outside the building. (Figure:4.T).

In this architectural and compositional framework, a stark departure from traditional design methodologies is observed. Rather than assembling predefined elements to construct a composite whole, this approach navigates fluidly and inquisitively across the thresholds of internal and external realms, between deliberate design intentions and emergent design outcomes.

This signifies a profound shift from conventional assembly-based design processes to one that is more exploratory, allowing for a more integrated and holistic architectural expression.

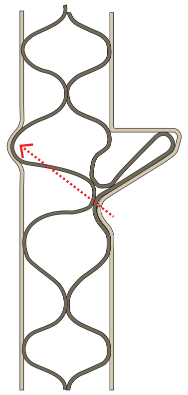


Figure:4.S

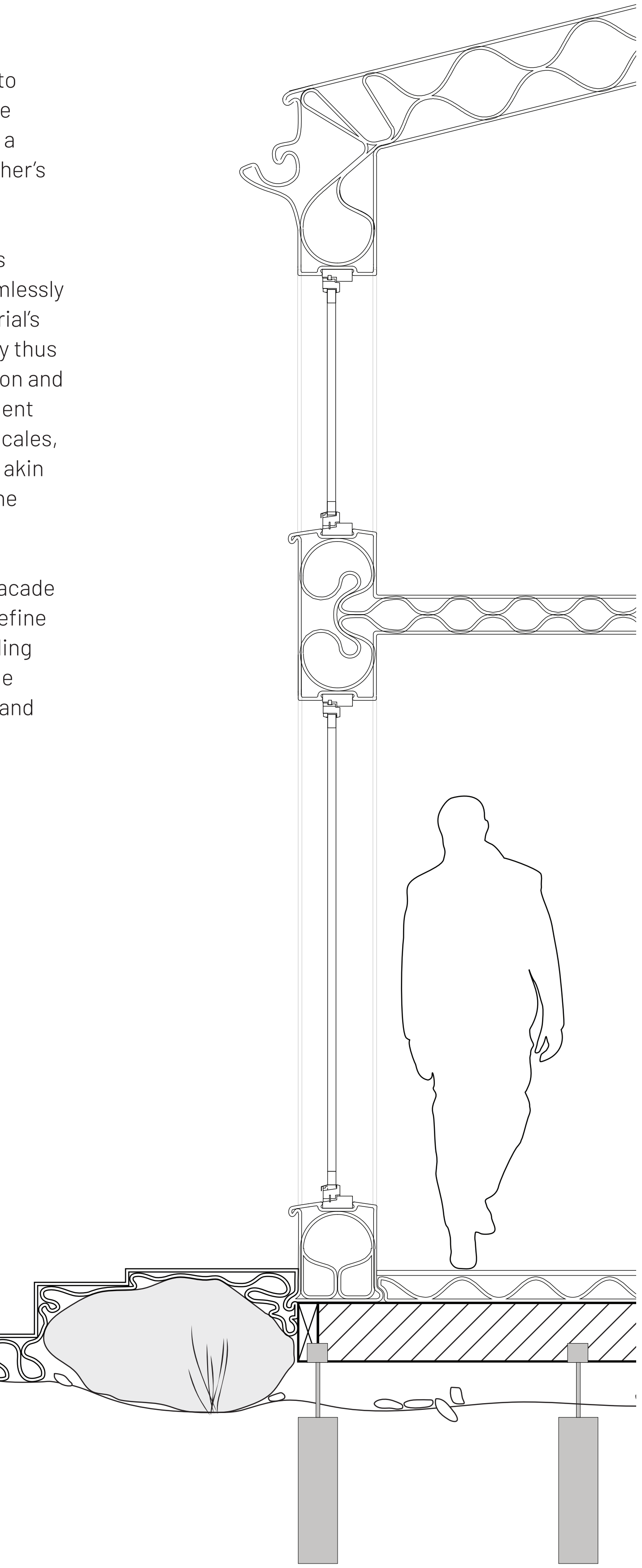


Figure:4.T

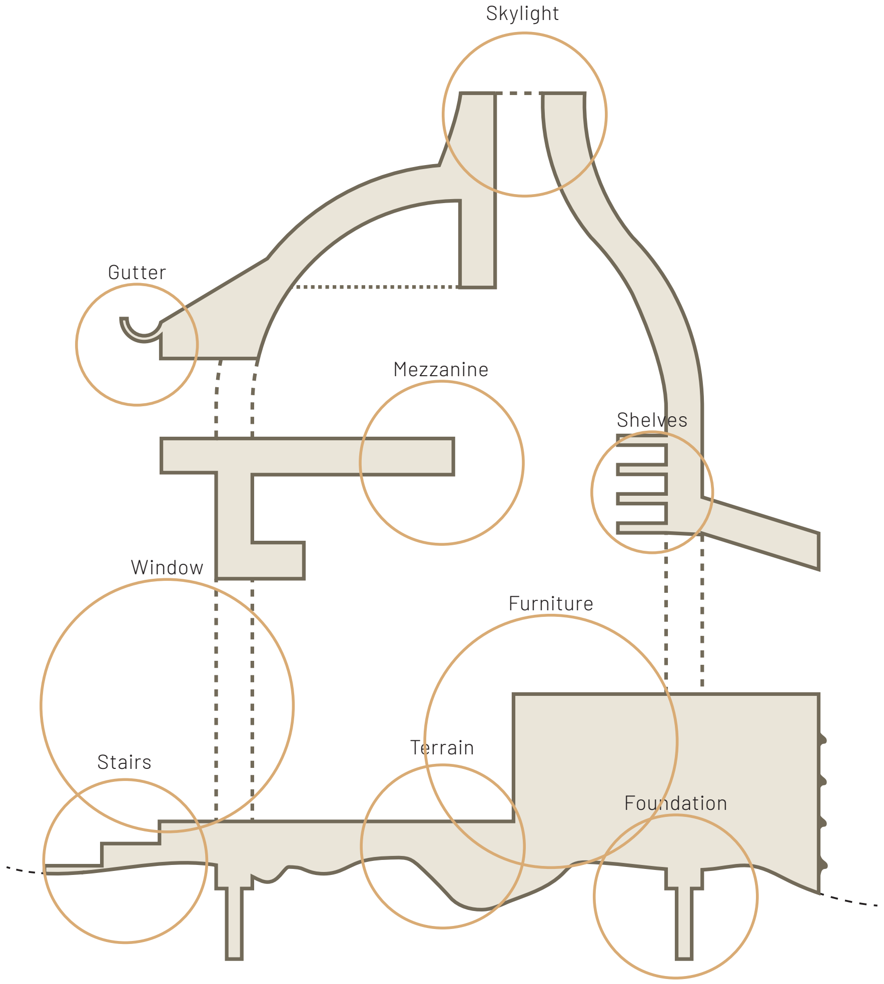


Figure:4.U
Integrated build features
How would a WOHN reality look like?

LOADING PERPENDICULAR

Loading perpendicular can provide loadbearing structures but only as self contained, monocque elements that are designed in plan. The result can be unique formal outcomes.

Designing and constructing with 3D printing technology in a perpendicular loading configuration involves adopting structural principles that facilitate self-supporting or self-bracing formations, typically achieved through single or double-layered print beads (Picture:4.b).

While the sandwich structure technique can be applicable in perpendicular loading, a more pronounced emphasis on self-sufficiency by design enhances the utilization of its inherent strengths. This method not only broadens the scope for freeform design and structural integrity but also optimizes material use.

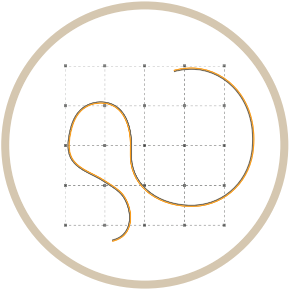
Picture: 4.d

PRINT
Single and double print beads

As outlined on page 37, employing this printing technique for load-bearing structures, while concurrently fabricating monocoque spaces, necessitates the design of shapes that distribute stresses and forces evenly across their surfaces (Figure:3.R) & (Figure:3.S) & (Figure:3.T) & (Figure:3.U), page 41.

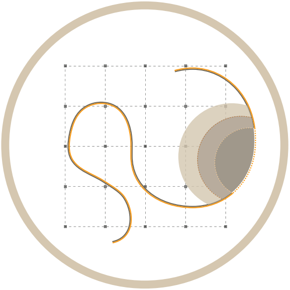
Combined with the restrictions in eaves and an uninterrupted extrusion page 36, a consequence of perpendicular loading is the delineation and reduced integration between the load-bearing framework and interior/exterior elements like stairs, canopies, and shelves.

This distinction informs the classification of the print technique into 3 design principles: Modularity, organic design, and; the combination of the two (Figure:4.Y).



a) Organic Design

b) Modular Design



c) Combination

Figure:4.V

MODULAR DESIGN //

While parallel loading facilitates the creation of monocoque structures with integrated functions in a single continuous print, perpendicular printing typically necessitates the production of multiple parts. For example, staircases or shelves must be printed in segments due to the printer's inability to execute skip or jump movements, necessitating subsequent assembly as depicted in (Figure:4.W).

There are two primary approaches to modular design: stacking layers vertically or attaching modules to one another.

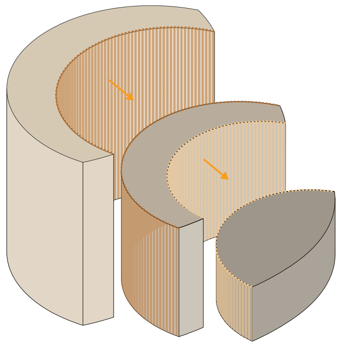


Figure:4.W
Staircase printed modular
Perpendicular loading

Stacked modules

The stacked layers approach constructs the design vertically, layer by layer, starting from the base and progressing upwards. It allows for functional components like shelves, stairs, or furniture to emerge incrementally from the primary wall or building structure, provided they remain within the constraints dictated by the maximum allowable eave (Figure:4.X). A limitation of this approach surfaces when flat horizontal planes are required, as in the cases of shelves, stair treads, or seating areas. Here, the module's printing must stop because the printer's nozzle cannot execute jumps (Figure:4.Y).

The strategy then involves designing an interlocking mechanism on the module, facilitating the secure attachment of subsequent modules atop the initial one (Figure:4.Z). This stacking principle leads to architectural forms composed of vertically accumulated modules, defining various functions and extensions as horizontal deviations within the overall structure exemplified in (Figure:4.AA) & (Figure:4.AB) & (Figure:4.AC) on page 62. This approach also highlights the critical role of fittings, recognizing them as potential points of vulnerability in the structural integrity of the construction.

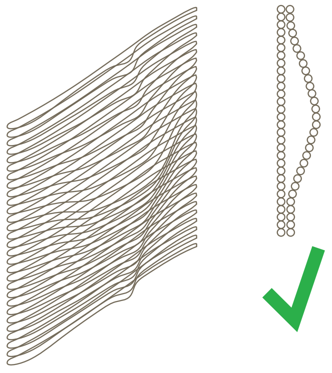


Figure:4.X
Closed circut
The print is coheseve, however no self

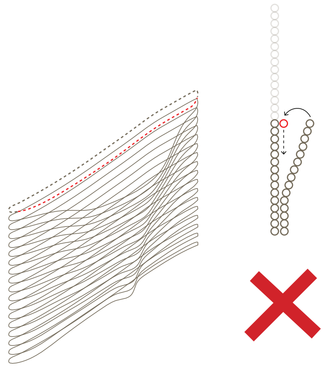


Figure:4.Y
No jumps
The print has an eave creating a bracket, due to the prints inability to print on thin air, the bracket must be in one of the ends of the print

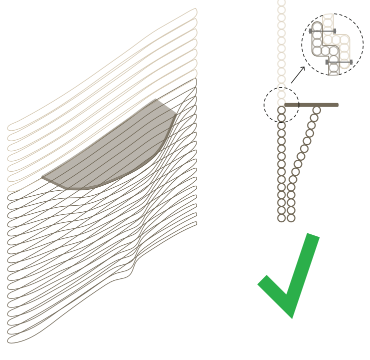


Figure:4.Z
Two(3) piece
Two peice print, and a shelf. To continue a print afte a barcket a new print is joined

Attached modules

An alternative approach involves a "design by scale" strategy, focusing on the sequential construction of the primary spatial elements, such as rooms or walls, which are printed first. Subsequent spatial features, like shelves and staircases, are then fabricated separately and attached directly to these primary elements (Figure:4.AA) & (Figure:4.AB) & (Figure:4.AC).

This method aligns with conventional interior construction practices, where the overarching spatial structure governs the integration of smaller, secondary components. A significant advantage of this approach is that the main structural framework remains independent of these smaller additions. Consequently, modifications or reconfigurations of these smaller elements do not necessitate alterations to the larger structure, affording flexibility for ongoing adjustments in the spatial organization and composition within the given environment over time.

As with the first technique, certain elements, such as staircase steps and shelves, may require the introduction of different materials due to the printer's limitations in jumping and printing overhang.

ADAPTIVE DESIGN //

The WOHN 3D printing technology unveils significant potential for innovating spaces through an adaptive design process. The technology's ability to manifest unconfined, adaptive forms opens up new avenues for spatial configurations, which are infrequently encountered within the realm of the sustainable architecture discourse.

The printer's adeptness in realizing organic transitions extends its influence across both the horizontal and vertical plane, facilitating the creation of intricate geometries, including doubly curved surfaces. This capacity for complex form-making is demonstrated in (Figure:4.AF) showcasing the broad scope and adaptability of this 3D printing technique.

This approach is particularly relevant in the design of walls and other large-scale building components that influence broader spatial relationships and organizational structures both within and surrounding a building. For instance, it facilitates the creation of unique curved plan layouts that not only can transform the spatial dynamics of an environment but also can respond precisely to the contextual setting and internal functions of a building, as illustrated in (Figure:4.AD).

Figure:4.AA
Shelf printed in parts: wall, bracket & cap
Perpendicular loading

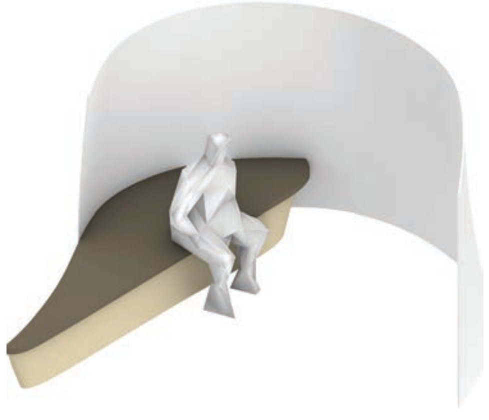


Figure:4.AB
Bench printed in parts: wall, frame & seat
Perpendicular loading

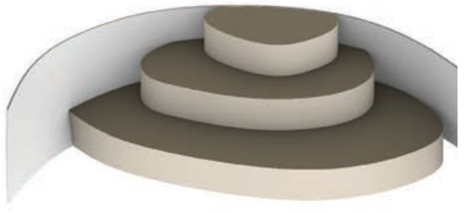


Figure:4.AC
Bench printed in parts: wall, frame & seat
Perpendicular loading

COMBINATIONS //

The true potential of this printing technique emerges from the synthesis of modular design and adaptive form-making. Traditionally, these two approaches are considered antithetical, as modularity typically does not coincide with the specificity and customization inherent in adaptive design. However, with WOHN's 3D printing capabilities, integrating these methodologies becomes feasible. An illustrative example is the ability to print customized staircases that seamlessly integrate with curved and adapted shaped slabs and walls (Figure:4. AF).

The combination of modular design principles with an adaptive form language is enabled by the plasticity and morphological flexibility of the building material. Modules can adapt and change, directly influenced by and mimicking adjacent elements. For instance, a modification in the curvature of a wall will automatically induce a corresponding change in the curve of an adjoining staircase or shelf (Figure:4.AD), all without incurring additional costs or resource expenditure. Similarly, the introduction of a small element, such as a piece of furniture, can translate into a significant spatial consequence in the building's structure (Figure:4.AE).

This ability to fluidly negotiate between elements and scales, functions and spaces, heralds new, transformative methods of designing and constructing architecture.

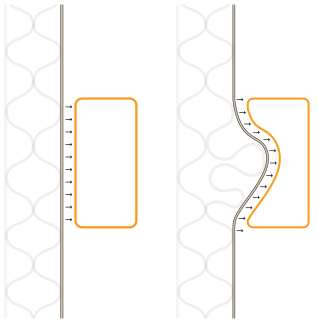


Figure:4.AD
Print adapting to concave object
Perpendicular loading

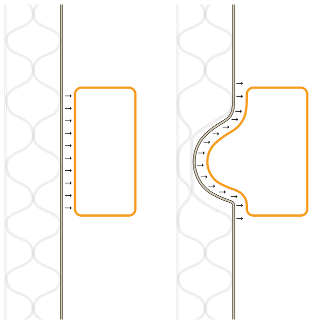


Figure:4.AE
Print adapting to convex object
Perpendicular loading

Figure:4.AF
Organic plan organizarion, printed modules
Perpendicular loading

ZOOM; LOADBEARING STRUCTURE
Print beads

PROTOTYPES

RESEARCH OF DESIGN QUALITIES AND CHALLENGES POSED BY WOHN 3D PRINTING, WITH A FOCUS ON AESTHETIC POTENTIALS - THIS CHAPTER CULMINATES IN DESIGN.

DESIGN SYNERGIES

Integrating perpendicular and parallel loading methodologies enhances design flexibility, architectural freedom, and structural versatility.

This awareness of the benefits of integrating components printed in alternate ways, guided the development of prototypes to be printed as the conclusion of this project.

To explore this, we developed three prototypes: one focusing on parallel loading, another on perpendicular loading, and a third that investigates the synergies created by combining these approaches.

Each prototype has been developed to articulate the primary qualities inherent in their respective loading methods. They are presented as works "in process," serving more as exploratory questions than definitive answers. These prototypes aim to identify potential strategies for working with large-scale 3D printing to establish new spatial and formal paradigms that are consequential to this specific technique.

Given that this manufacturing approach and material composition are highly circular—offering significant CO2 mitigation and the potential for scalability and customization—this chapter seeks to reconceptualize the aesthetics of sustainable architecture.

How can sustainable architectural aesthetics be reimagined in light of these innovative technologies and methods?

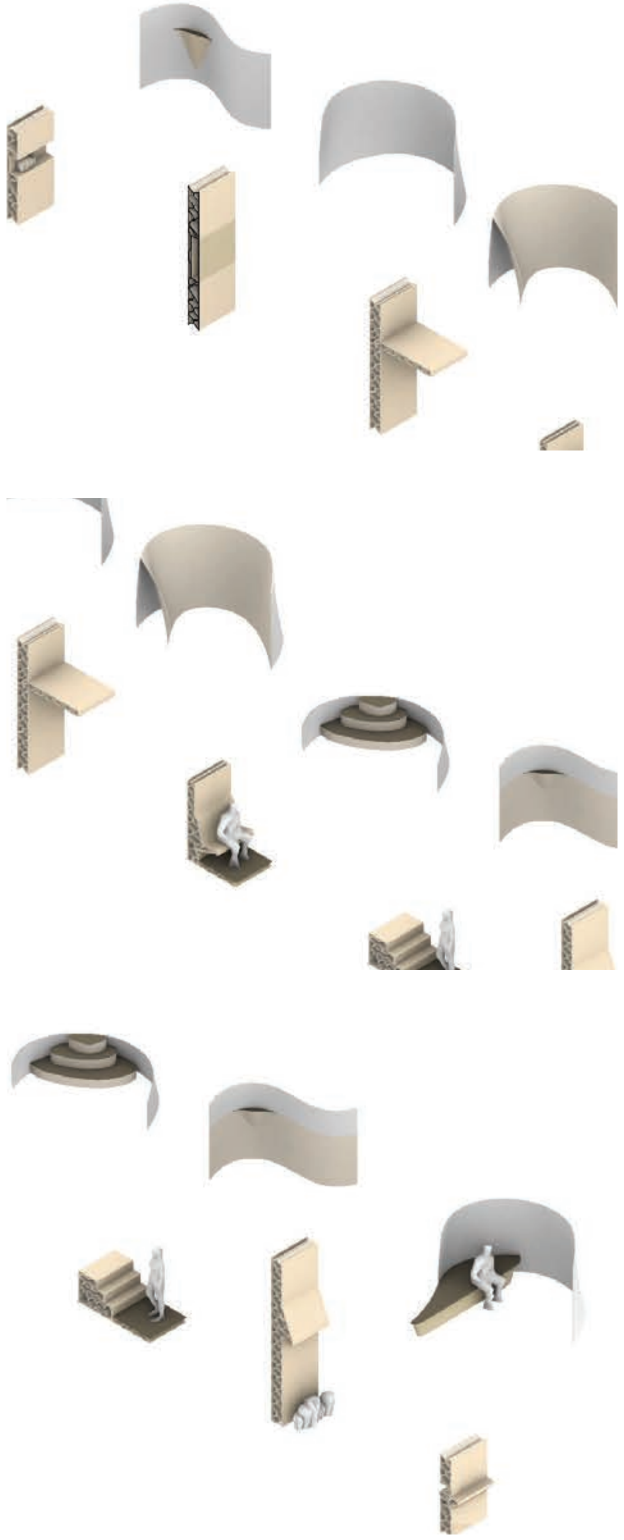
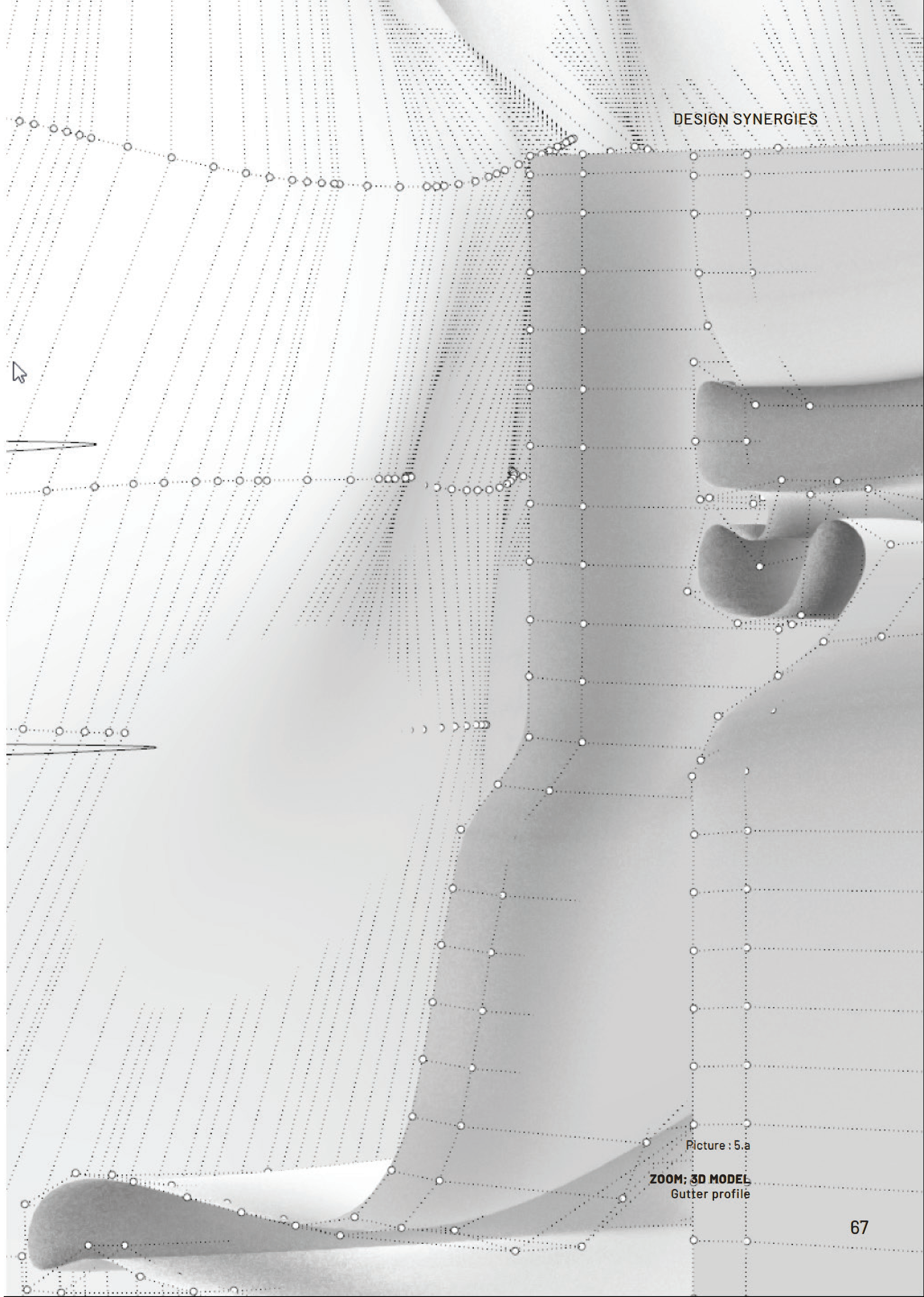


Figure:5.A

Assembly of elements
Tools for design synergies



Picture : 5.a

ZOOM; 3D MODEL
Gutter profile

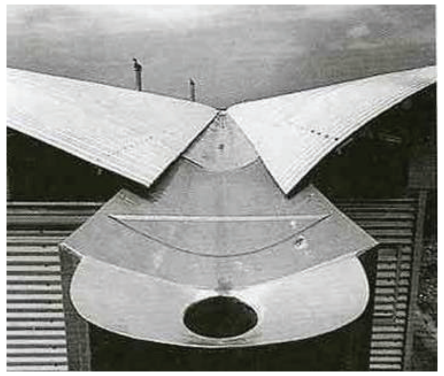
HYBRID SURFACES

A functional surface that, within a single print, can combine spatial, technical, programmatic and poetic considerations.

Parallel loading facilitates the printing of load-bearing elements as sectional components within larger structures, defining design parameters as slices of a structure. This method significantly influences the relationship between interior and exterior spaces, merging traditional construction methods with cutting-edge 3D printing technologies. The integration of structural components with spatial configurations promotes multifunctional environments, characterized by cohesive aesthetics and spatial coherence.

This approach imbues surfaces with the potential to integrate functions by designing with subtle spatial dynamics and protrusions. Traditional categories such as walls, benches, and gutters are redefined and merged, resulting in the creation of both familiar elements and new hybrids. These hybrids, which are functional, spatial, and aesthetic amalgamations, challenge our conventional understanding of function and space, as well as the aesthetics associated with sustainability. They introduce an element of the 'unknown,' filled with the eeriness of undefined possibilities, which holds significant potential for reinterpretation into 'something else.'

These hybrid surfaces, emerging as consequences of innovative design processes, prompt us to contemplate 'what could be.' They ignite our imagination and curiosity, reintroducing a sense of playfulness into architecture. This is not merely an aesthetic endeavor but a drive towards embracing circularity and sustainability, questioning and expanding the roles of architectural elements in sustainable design.



Picture: 5.b
Gutter as prominet detailing
Glenn Murcutt

Picture: 5.c
Integrated bench
Gunnar Asplund

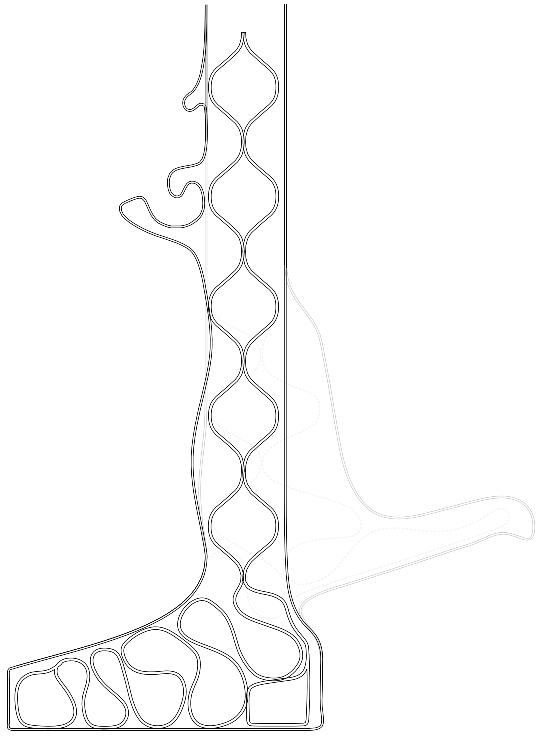


Figure:5.B
Section / gutter in front
1:20

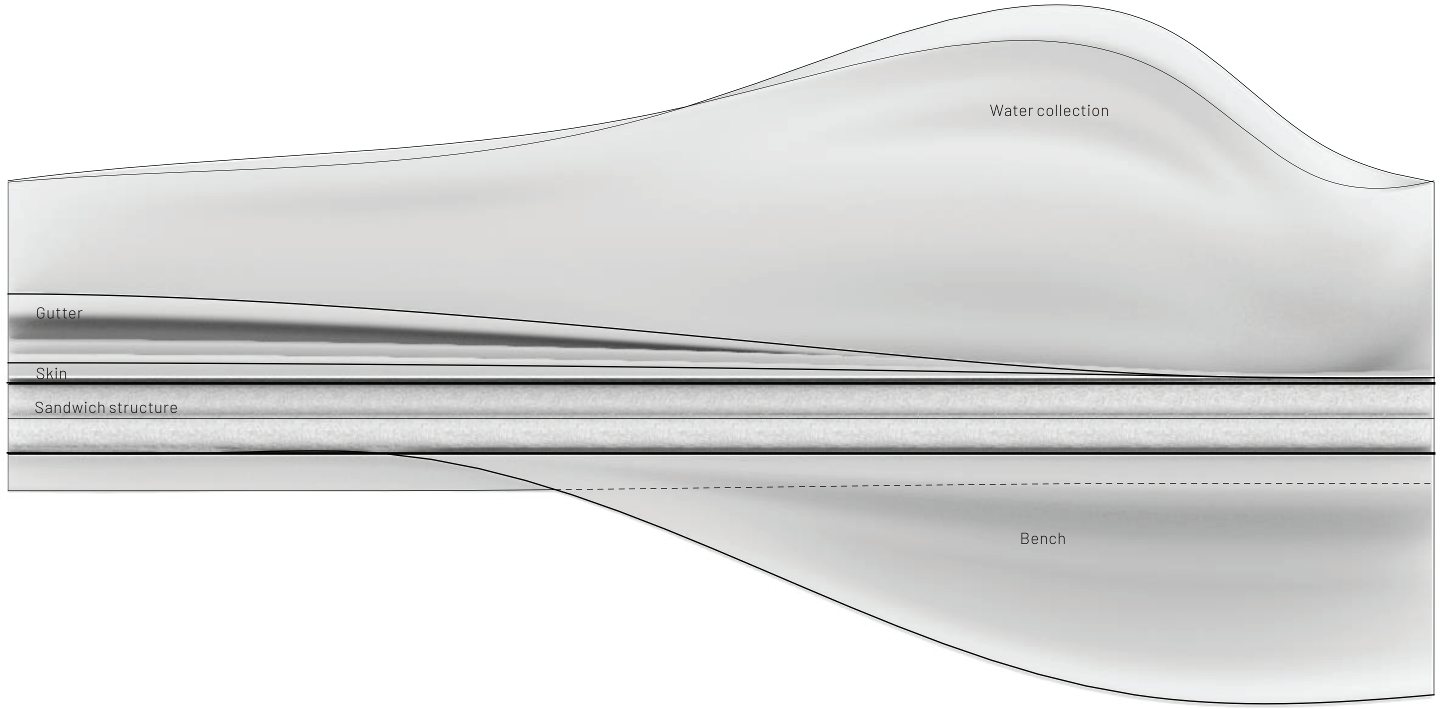


Figure:5.C
Plan
1:20

Figure:5.D
Gutter elevation
1:20

Figure:5.E
Abstract elevation
1:20

Figure:5.F

Isometric drawing
Noth west

Figure:5.G
Isometric drawing
South east

Figure:5.H
Isometric drawing
South west

Figure:5.I
Isometric drawing
North east

Figure:5.J
Perspective
Movement of the gutter

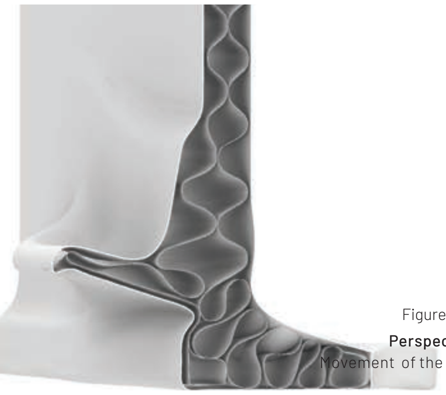


Figure:5.N
Perspective
Movement of the seat

Figure:5.K
Perspective
Gutter profile

Figure:5.O
Perspective
Seat profile

Figure:5.L
Perspective
Integration of water way

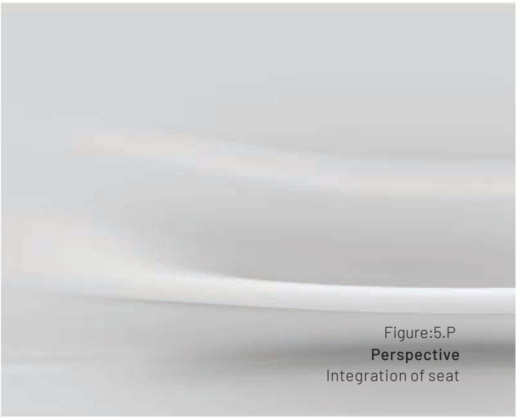


Figure:5.P
Perspective
Integration of seat

Figure:5.M
Close up
Water collection

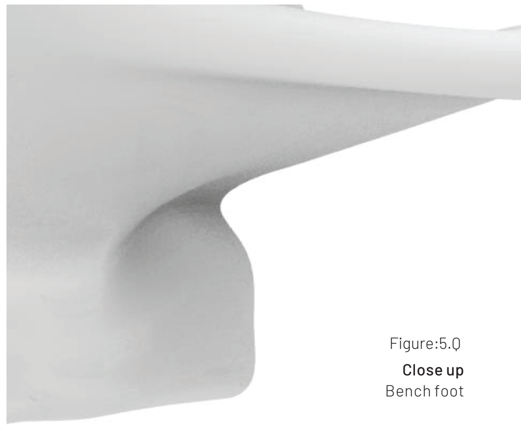


Figure:5.Q
Close up
Bench foot

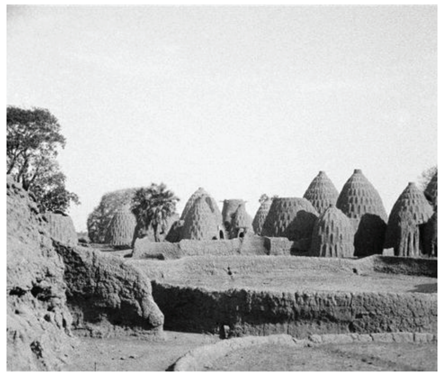
POETIC SPACES

Contemporary 3D printing technology affords the opportunity to create building structures that poetically bridge space and time, reconnecting with ancient prehistoric architectural forms.

Printing perpendicular, layer-by-layer, mirroring traditional coil pottery techniques, establish a spatial and temporal link to building structures from eras predating the formalization of architecture as a profession. These spaces are distinguished by their simple, poetic configurations, which optimally utilize natural light, air circulation, and other vernacular principles, with gravity serving as a foundational structural component. They frequently adopt dome or cone shapes, crafting serene environments that promote deceleration and contemplation.

Such constructions have become scarce in modern building practices due to their deviation from standard construction methods and the predominance of mass-produced materials. The deviation from standardization typically equates to increased complexity and cost. However, with today's 3D printing technology, this dynamic is transformed. The 3D printer is indifferent to the regimes of standardization—as long as the structures are architecturally sound, spaces designed with an emphasis on spatial and formal poetry can be constructed as readily, if not more so, than standardized buildings.

This technological advancement prompts a significant inquiry into typologies conducive to sustainable building practices, particularly given that structures like these are inherently limited in size and scale. Given the circular nature of the materials and manufacturing techniques discussed in previous chapters, we must reconsider the spatial implications and consequences of designing such spaces. Poetic spaces designed for a more contemplative existence not only challenge conventional architectural practices but also inspire a deeper exploration of sustainable and meaningful architectural solutions.



Picture: 5.d
Clay Obos of the Musgum people
Pouss, Cameroon

Picture: 5.e
Twisted Brick Shell Concept Library
HCCH Studio

Figure:5.R
Elevation
Openings

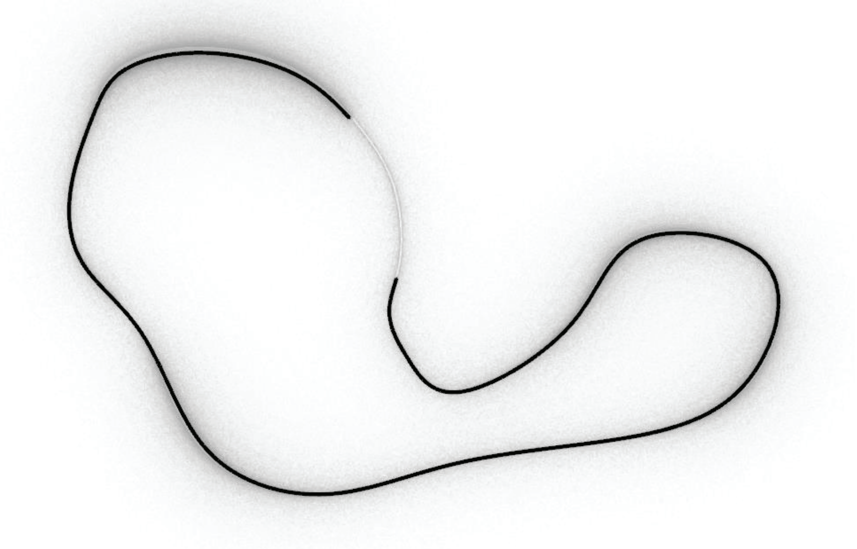


Figure:5.S
Plan / 10cm

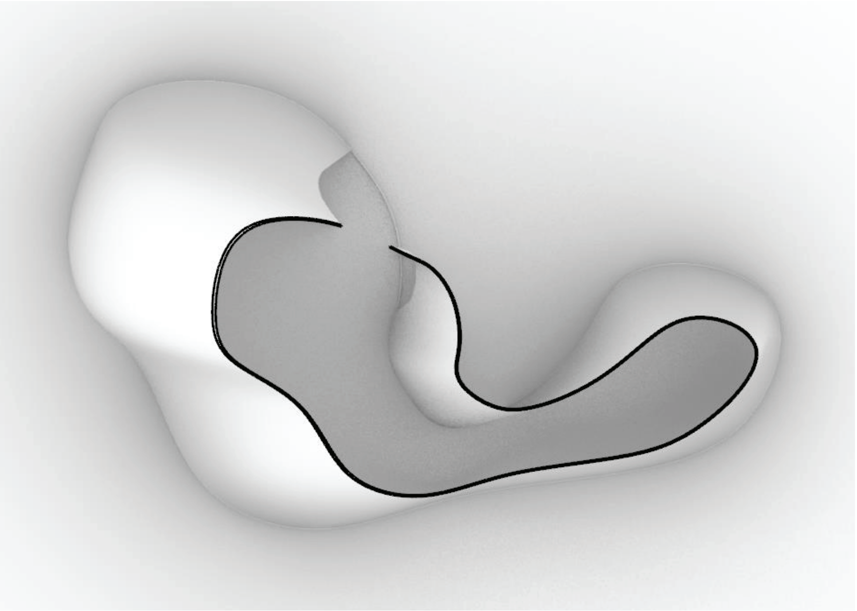


Figure:5.T
Plan / 100cm

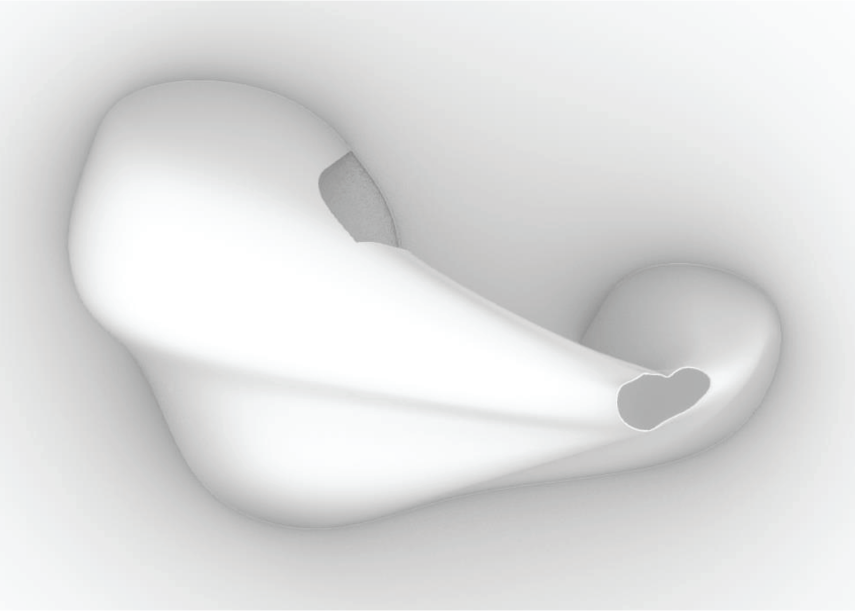


Figure:5.U
Plan roof

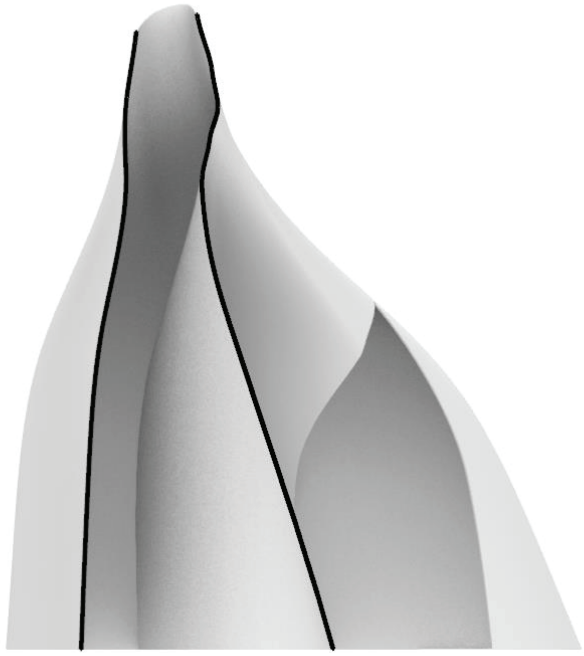


Figure:5.V

Rendered section

Figure:5.W

Rendered elevation
Openings

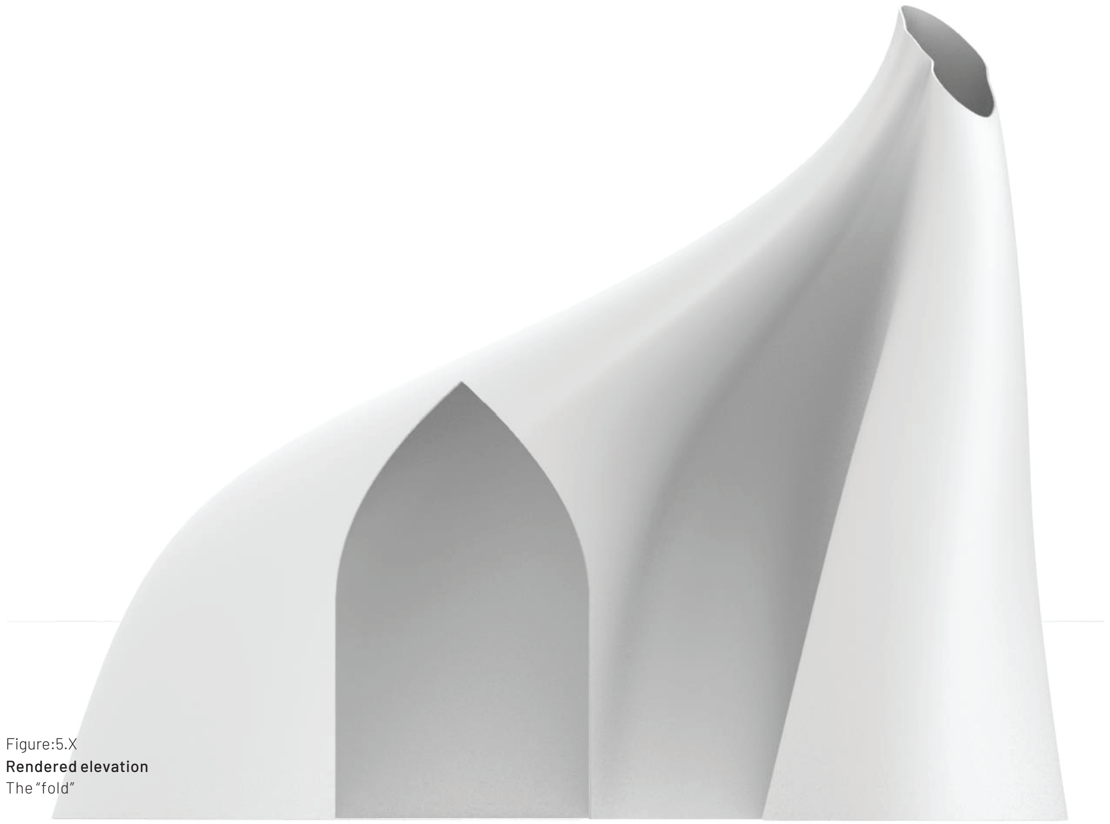


Figure:5.X
Rendered elevation
The "fold"

Figure:5.Y

Rendered section

Figure:5.Z
Rendered elevation
Enclousre

Figure:5.AA
Rendered Elevation
The "fold"

A FLEXIBLE SYSTEM

Combining different printing techniques opens new horizons for aesthetics in sustainable architecture.

As discussed in the preceding sections, printing either parallel or perpendicular to the load paths offers distinct advantages. Printing perpendicular allows for the creation of spaces with almost unlimited formal flexibility, while parallel printing produces robust structures capable of supporting a vast array of functional elements.

By integrating both techniques, it is possible to construct habitable spaces that harness the strengths of each approach. This synergy results in environments where the material quality and directional orientation are intricately linked to their functional performance. This integration marks a significant conceptual advance in the discourse on aesthetics and 3D printing, moving beyond the notion of infinite flexibility to acknowledge that, like any traditional material, there is an inherent relationship between material patterns, forms, and their intended functions.

This understanding paves the way for further exploration in subsequent phases of development, where the initial "biopsies" of this approach can be scaled up and evolved into fully functional, habitable spaces. This progression underscores the potential of 3D printing to redefine architectural form and function in the context of modern sustainable practices.

Such a synthesis of printing technologies not only challenges the traditional boundaries of architectural design but also enhances the sustainability of building practices by optimizing material use and reducing waste. Ultimately, the combination of these printing methods exemplifies a transformative approach in architecture, where innovation meets environmental stewardship, pointing the way toward future developments in the field.

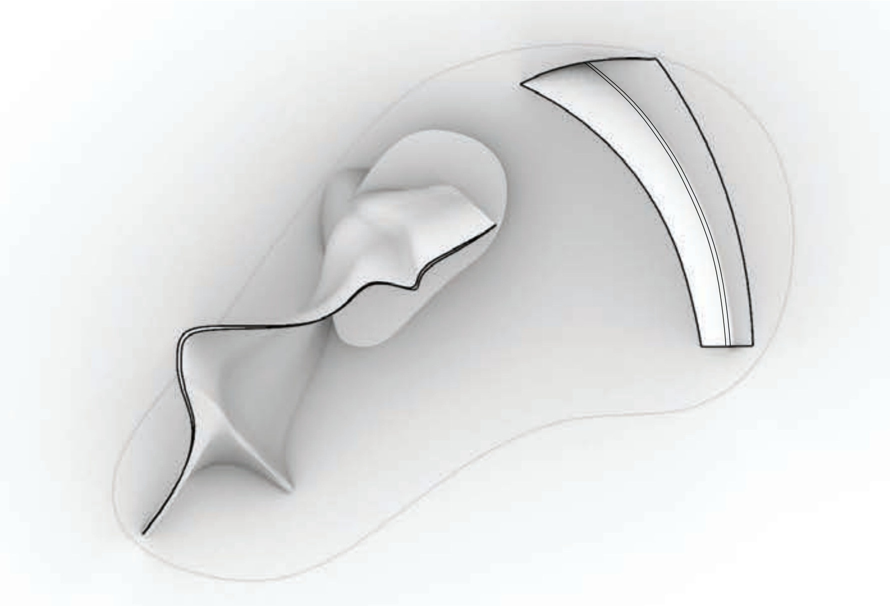
Picture: 5.f
Plastic Pavillion
Terroir

Picture: 5.g
TWIN CEMETRY SPACES
Hans Meas

Figure:5.AB
Persepctive
Spaciclity, right

Figure:5.AC
Persepctive
Spaciclity, left

Figure:5.AD
Plan / 10cm



Plan / 220 cm

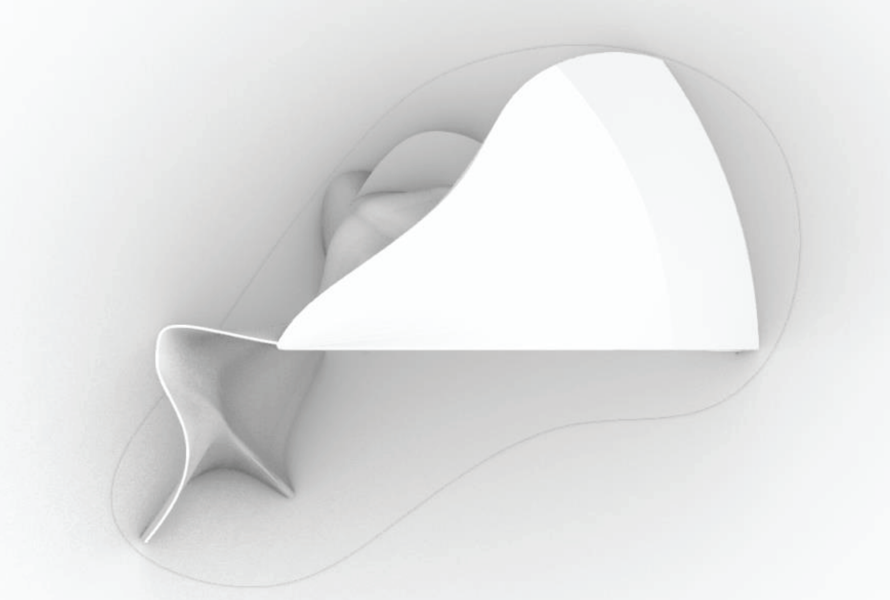


Figure:5.AF
Plan / Roof

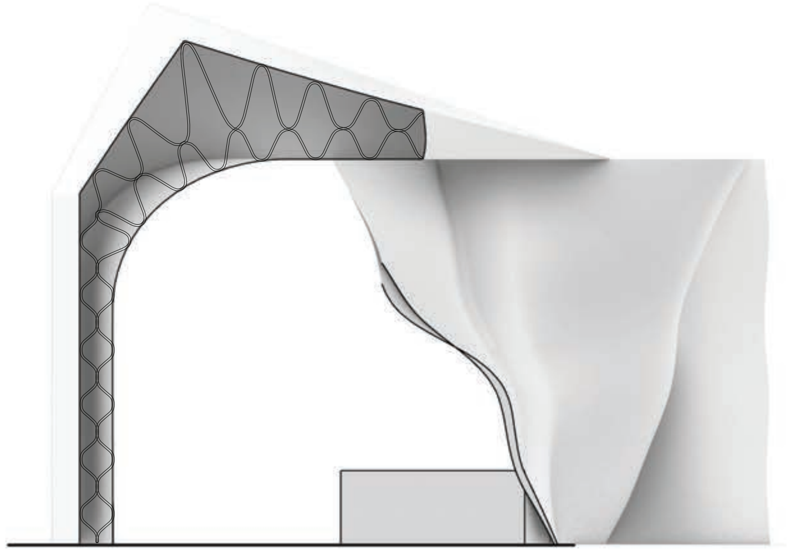


Figure:5.AG
Section
1:50

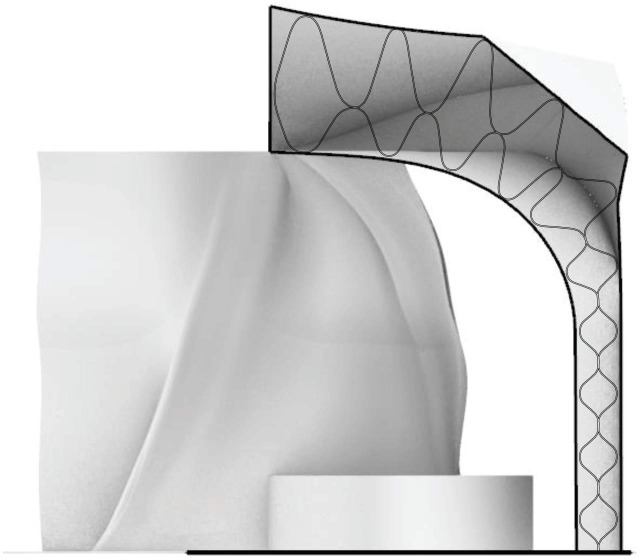


Figure:5.AJ
Section
1:50

Figure:5.AH
Perspective
Internal space

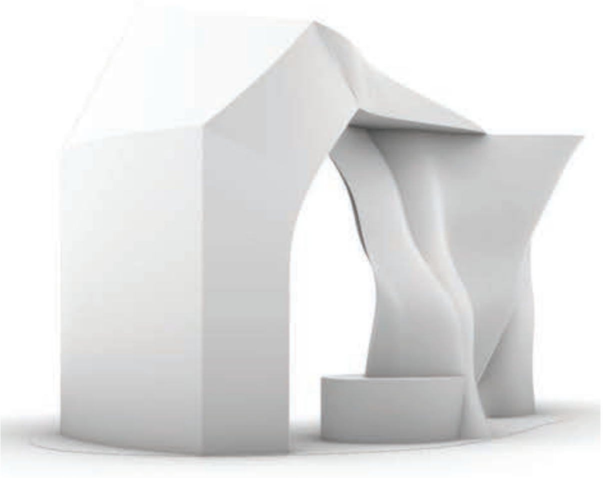
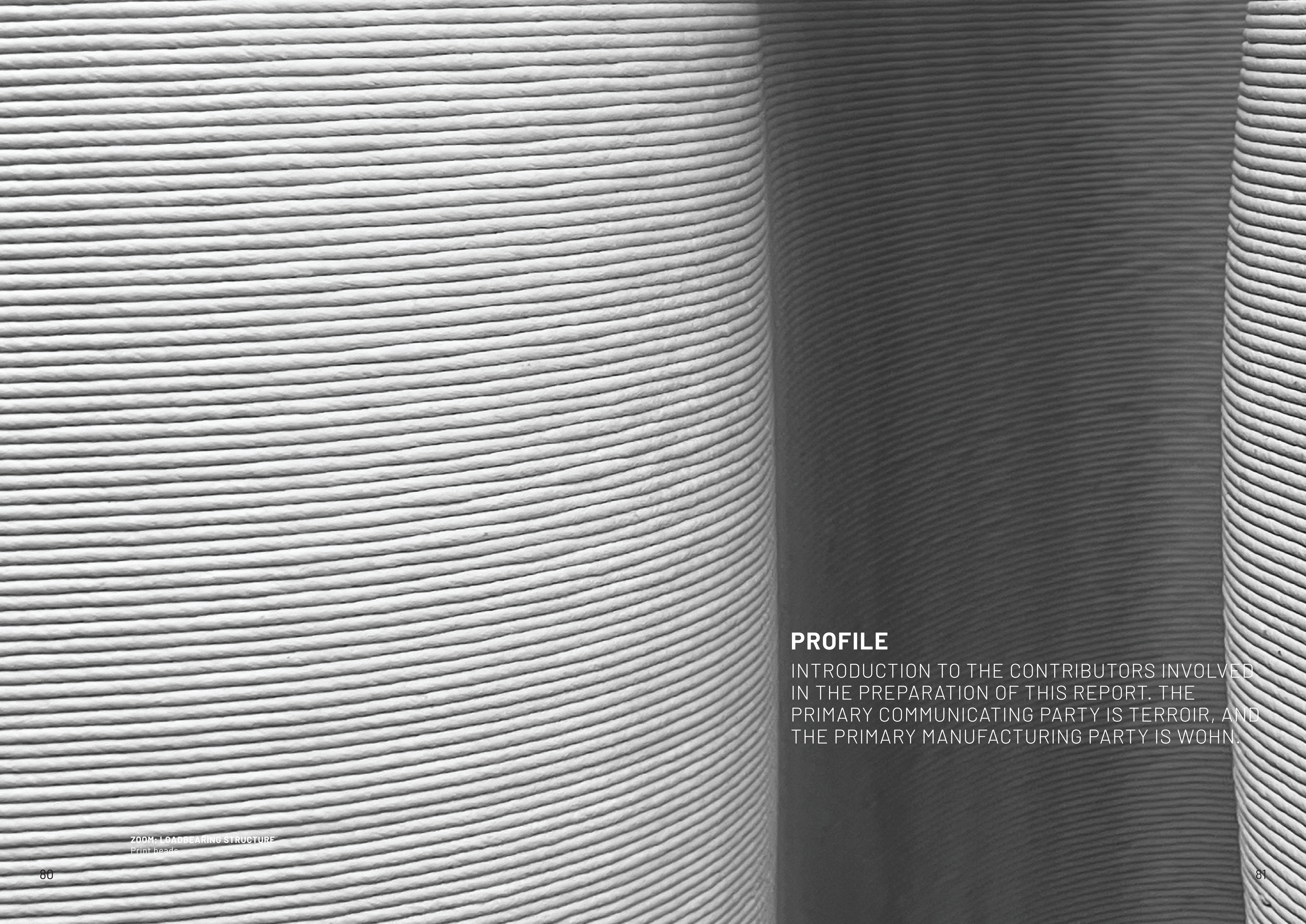


Figure:5.AI
Perspective
Exchange between loadings

Figure:5.AK
Perspective
Reaching directions

Figure:5.AL
Perspective
External space



ZOOM; LOADBEARING STRUCTURE
Print beads

PROFILE

INTRODUCTION TO THE CONTRIBUTORS INVOLVED IN THE PREPARATION OF THIS REPORT. THE PRIMARY COMMUNICATING PARTY IS TERROIR, AND THE PRIMARY MANUFACTURING PARTY IS WOHN.

TERROIR APS
ARCHITECTS

"TERROIR was named and founded with an ambition to show care for the places we build and the people who inhabit them. We have discovered that when we care for both people and places, it often leads to unique ways of understanding our shared future."- prof. Gerard Reinmuth, co-founder and Director at Terroir.

Established in Australia in 1999 and active in Denmark since 2010, TERROIR have a portfolio of several internationally award-winning projects. The company specialize in creating building projects of public relevance deeply rooted in and in close dialogue with local communities. TERROIR takes research seriously in their practice and seizes the opportunity to contribute to the sustainable transformation of the construction industry with each project.

The company consist of a collective of architects and urban designers employing approximately 40 people spread across three offices in Copenhagen, Sydney, and Hobart. Their presence in both Australia and Denmark brings international and cross-cultural perspectives and experiences to all projects, allowing them to view local projects from a global perspective. Drawing from Australia's multicultural composition of nationalities, minorities, indigenous peoples, and immigrants, TERROIR has extensive experience engaging in and facilitating complex processes that consider diverse positions and interests.

TERROIR engage in close collaborations across industries and professions, where they can contribute with their artistic and architectural expertise in encounters with other people, their practices, and knowledge.

TERROIR also maintains close ties with the educational environment in both Australia and Denmark. Staff members teach at institutions such as the Royal Danish Academy of Fine Arts, School of Architecture, and the University of Technology Sydney, allowing TERROIR to stay updated with the latest knowledge in urban planning, architecture, and sustainability.

Picture : 5.a

TERROIR OFFICE
Hobart

WOHN.DK APS
MANUFACTURERS

WOHN A/S is a startup company established during the COVID-19 lockdown in 2020. The company has developed a method to address the demand for innovative construction practices by introducing new principles for house construction: scalable, sustainable, and cost-effective. By combining the principles of 3D printing with industrial waste, WOHN has created a construction technique that focuses on additive and adaptive methods, enabling the creation of highly specialized and precise solutions that are also affordable and scalable. Furthermore, WOHN prints with an innovative material composite, utilizing waste wood and recycled plastic as components for the large scale 3D prints.

The company currently comprises the two founders: Morten Bove as CEO and Matúš Uríček as CTO. Morten, an experienced entrepreneur, also serves as a startup mentor at the Danish Technical University and Tech Nordic Advocates. Matúš is a structural engineer, specialized in transformative technologies. He has a background in Additive Manufacturing as an independent researcher.

WOHN belives in urbanization as a driving force for sustainable growth and equality. As the population in cities grows, the cities face challenges in meeting the demand for affordable and sustainable housing. WOHN is reimagining the approach to housing: the way we build, live, and organize our homes. They envision a future for housing based on adaptability, accessibility, sustainability, and demand.

What distinguishes WOHN is their construction methodology, employing a 3D printer to fabricate houses and load-bearing structures. WOHN's 3D printer manufactures these using recycled plastic waste and waste wood, significantly reducing the construction's overall CO2 footprint by over 90%[4] and sequestering 4 tons of waste per 20 square meters of housing.

Picture : 3.a

MORTEN BOVE (CEO) & MATÚŠ URÍČEK (CTO)
Herflumagle

ENDNOTES

1 BUILD RAPPORT, (2023) Agnes Garnow, Buket Tozan, Lea Hasselsteen Nielsen, Liv Kristensen Stranddorf, Kin Sun Tsang, Camilla Ernst Andersen, Christian Grau Sørensen og Harpa Birgisdóttir (2024.03.11) via; “Boligbyggeri-fra-4-til-1-planet-25-Best-Practice-Cases.” [Insert Access Date], https://www.boligbyggeri-fra-4-til-1-planet-25-best-practice-cases.com.

2 MIT Sloan School of Management. (2017). (2024.03.11) “Additive Manufacturing Explained.” via https://mitsloan.mit.edu/ideas-made-to-matter/additive-manufacturing-explained.

3 Loading in the print direction” refers to the way force or weight is applied to a 3D printed object in alignment with the direction in which the object was printed. In 3D printing, layers are built up in a specific direction (the print direction). When a load (force or weight) is applied in the same direction that the layers are printed, the object is said to be loaded in the print direction.

4

THANKS.