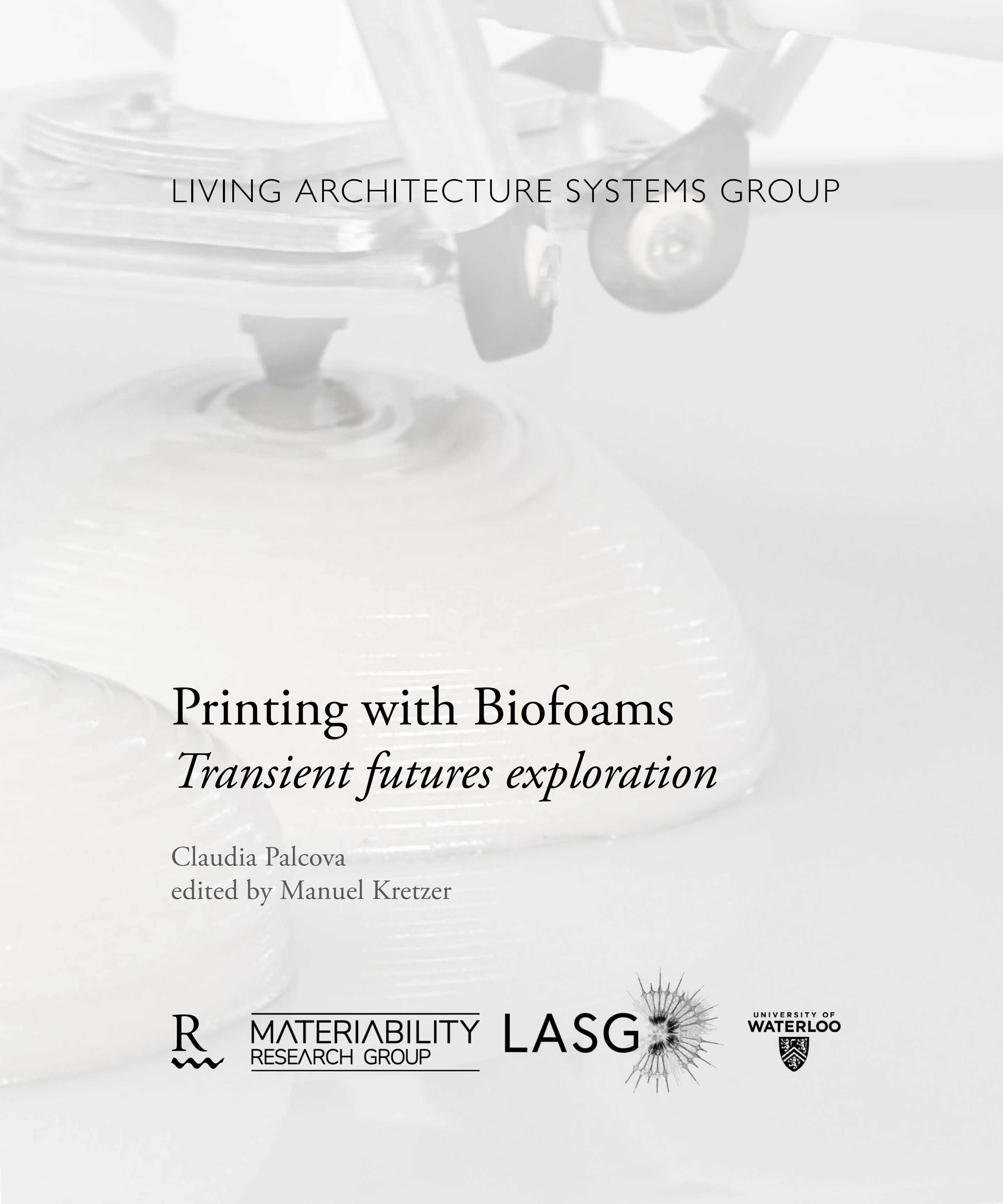


LIVING ARCHITECTURE SYSTEMS GROUP

Printing with Biofoams

Transient futures exploration

Claudia Palcova
edited by Manuel Kretzer

MATERIABILITY RESEARCH GROUP
LASG
UNIVERSITY OF WATERLOO

LIVING ARCHITECTURE SYSTEMS GROUP

Printing with Biofoams

Transient futures exploration

Claudia Palcova
edited by Manuel Kretzer

Publisher: Riverside Architectural Press, www.riversidearchitecturalpress.ca

Title: Printing with Biofoams: Transient futures exploration
Authors: Claudia Palcova, edited by Manuel Kretzer
Living Architecture Systems Group, issuing body.

Description: Living Architecture Systems Group folio series | With Materiability Research Group. Includes Index.

Identifiers: Canadiana 20220424047 | ISBN 978 -1- 988366 - 41- 8 (softcover)

Subjects: LCSH: Foamed materials. | LCSH: Biopolymers. | LCSH: Three-dimensional printing.

Design and Production: Claudia Palcova, Manuel Kretzer, Philip Beesley, Timothy Boll, Adrian Chîu, Bianca Weeko Martin

Classification: LCC TA418.9.F6 P35 2022 | DDC 668.4/93—dc23

This book is set in Garamond, Swis721 BT and Zurich BT.

Social Sciences and Humanities Research Council of Canada
Conseil de recherches en sciences humaines du Canada
Canada

MATERIABILITY RESEARCH GROUP
LASG
UNIVERSITY OF WATERLOO

Supported by: Materiability Research Group, Hochschule Anhalt, Philip Beesley Studio Inc., University of Waterloo. This work has received funding from the Hochschule Anhalt 2022 Materiability Research Group.

Contents

Introduction

Snow, soil, stone, wood, straw, plaster, leather, bones ...

First forms of constructed human settlements were made of locally sourced natural materials which were gradually manipulated and applied to provide shelter from external forces. Whether they were made of solid, stable and durable materials such as stone or flexible, adaptable and gradually biodegradable materials such as leather, early settlements were comprised of rapidly constructed temporary structures which accommodated nomadic communities' frequent forages for food and water supplies. As humans began to cultivate land for farming, the demand for a settled lifestyle started to grow, changing both the physical and the psychological role of a shelter. Stability, predictability and durability[1] increasingly modified the concept of a dwelling, leading to a current construction industry standard of a 50-100 year technical building lifespan[2]. However, ideas of mobility, adaptability and temporality remain frequent disrupters of this rigid building pattern. Flexible, modular systems proposed throughout mulitple architecture and design ideologies, including Structuralism, Metabolism, High-Tech and Parametricism utilise the newest available technologies to expand the possibilities of responsive, user-centred environments. To this day, concepts of Utopian and Paper architects of the 60s and 70s contribute to challenging conventional notions of architecture, by treating buildings not as objects but as "instruments of societal change"[3]. Encouraging free, dynamic and responsive relationships between humans and their built environments, English architectural critic Reyner Banham expressed his visions for future urban settlements in 1957, stating

"*The fundamental characteristics of futuristic architecture will be expandability and transience. Our house will last less time than we do, every generation must make its own city*"[4].

Preceding page

Biofoam surface prototype utilises unit density and scale gradients to achieve a spectrum of zonal properties and behaviours

Scale 120 x 120 x 35mm

1 Le Corbusier, 2009. Towards a New Architecture. Miami: BN Publishing

2 Marsh, Rob 2017. 'Building lifespan: effect on the environmental impact of building components in a Danish perspective' *Architectural Engineering and Design Management*, 13:2, p.80-100, DOI: 10.1080/17452007.2016.1205471

3 Spatial Agency 2011. *1960s Utopian Groups*, accessed 02 July 2022, <https://www.spatialagency.net/database/why/political/1960s.utopian.groups>

4 Banham, Reyner 1957. 'Manifesto' *Journal of the Royal Institute of British Architecture*, vol. LXIV, no 4, p. 129-139

Confronted with surging global warming, waste pollution and radical global urbanisation with more than half of the population residing in cities[5], it is only appropriate to revisit these ideas of flexible[6,7], responsive[8] and affordable[9] architectures to reevaluate how the current design and construction practices could serve as instruments for a positive environmental impact. Michael Pawlyn and Sarah Ichioka talk about paradigm shifts from politically charged sustainable design to regenerative design[10], highlighting the importance of learning from natural systems and behaviours and applying them to the way we design and construct our environments[11, 12]. While exploring a variety of structural adaptations and novel material applications to reduce our impact on the environment and implement circular design solutions, Pawlyn and Ichioka also consider the intangible shifts in the way we occupy and connect with our environments. Projects such as Los Angeles Eco-Village or One Brighton housing development encourage community living where the sharing and exchange of tools and items reduce the dependence on countless possessions and extensive storage spaces - an idea proposed earlier in the 1960s by Buckminster Fuller who viewed possessions as a burden to the free and dynamic movement of urban nomads[13].

In an attempt to expand the diversity, inclusivity and flexibility of urban settlements without leaving a permanent mark on the environment, *Printing with Biofoams: Transient futures exploration* investigates novel regenerative materials that have the ability to respond and adapt to changing external as well as internal conditions. Manuel Kretzer describes smart materials[14] as dynamic, responsive and adaptable in their nature, noting the importance of understanding the full potential of these novel materials and applying them in ways that expand our experiences and connection with the built environment rather than trying to confine them to the restricted material applications and performances of the standardised construction industry. While studios such as BIOHM, Blast Studio, or Christien Meindertsma, to name a few, study, develop and implement regenerative, circular materials that reimagine the way we construct and maintain

5 Seto, K. C., Dhakal, S. et al. 2014. Human Settlements, Infrastructure and Spatial Planning. In: Climate Change 2014: Mitigation of Climate Change Contribution of Working Group III to the Fifth. p 929

6 Gijsbers, Roel 2006. Towards adaptability structures to extend the functional lifespan of buildings related to flexibility in future use of space. Eindenhoven University

7 Leupen, Bernard 2005. 'A New Way of Looking at Flexibility' *Open House International*, Vol. 30 No. 1, 2005: 55-61. https://doi.org/10.1108/OHI-01-2005-B0008

8 Beesley, Philip 2010. Hylozoic Ground: Liminal Responsive Architecture: Liminal Responsive Architecture, Riverside Architectural Press

9 Brown, David, et al. 2004, The Home House project: the future of affordable housing, Cambridge; The MIT Press

10 Ichioka, Sarah and Pawlyn, Michael 2022. Flourish, Design Paradigms for Our Planetary Emergency. Triarchy Press. p. 78

11 Benyus, Jenine, M. 2002. Biomimcry: Innovation inspired by nature, Harper Perennial.

12 Kapsali, Veronika 2021. Biomimetics for Designers: Applying Nature's Processes & Materials in the Real World, Thames and Hudson Ltd.

13 Fuller, R. Buckminster 1967. Operating Manual For Spaceship Earth, Southern Illinois University Press. p.165

14 Kretzer, Manuel 2014. ALIVE: Advancements in Adaptive Architecture. German National Library p. 72 - 77

our environments, blurring the boundaries between the synthetic and the natural, studios such as EcoLogic Studio, Terreform One or Tomas Saraceno Studio explore future scenarios where novel materialities, systems and structures emerge from close collaborations with other living organisms, ranging from macro to microorganisms, to create a symbiogenetic[15] living environment. Regenerative, recyclable, reusable and compostable materialities in architectural contexts are fundamental for advancements in temporary interventions, expanding the potential for infinite adaptations, modifications and applications while eliminating fossil fuel extractions, minimising greenhouse gas emissions and waste pollution.

Exploring the potential of transient materialities in the context of 21st Century urban architectures, biopolymers are the main subject of this research due to their low energy and resource consumption, recyclability and compostability. Advancements in biomaterial sciences continually introduce a great spectrum of materials ranging from thin, flexible biofoils to pressure-resistant, water-proof and fire-proof building blocks[17,18,19]. Different types of renewable biomass can be utilised, including protein, starch and cellulose to suit a variety of functions and applications[19, 20, 21]. While there has been a noticeable increase in biomaterial implementations in everyday products, the materials' susceptibility to distortion and degradation caused by changing environmental conditions leads to limited large-scale and long-term applications. The following paper views this seeming unsuitability of biopolymers for architectural applications as an opportunity to rethink our understanding and relationship with the built environment. It questions our established needs and wants while emphasising symbiogenetic relationships between permanent and transient architectures as instrumental for societal and environmental change. The versatile, adaptable and accessible nature of biopolymers opens up possibilities for alternative materials, methods and technologies which would enable the construction of non-invasive and non-toxic temporary environments to expand the role and function of already existing sites.

15 Symbiogenesis "appearence of new tissues, new organs, physiologies or other new features that result from protracted symbiotic assosiations"[16]

16 Margulis, Lynn 2004. 'Serial endosymbiotic theory (SET) and composite individuality' *Microbiology Today*, p.172

17 Solanki, Seetal 2018. Why Materials Matter. Prestel, Verlag, Munich

18 Franklin, Kate and Till, Caroline 2018. Radical Matter - Rethinking materials for a sustainable future. Thames&Hudson, Inc. New York

19 Peters, Sascha and Drewes, Diana 2019. Materials in Progress: Innovatins for designers and architects. Birkhauser Verlag GmbH, Basel

20 Kabasci, Stephan 2013. Bio-Based Plastics: Materials and Applications, John Wiley & Sons, Ltd

21 Materiability Research Group 2020. *Materiability* accessed 02 July 2022, <https://materiability.com>

22 Materiom 2022. *Materiom*, accessed 02 July 2022, <https://materiom.org>

23 Schunemann, Esteban 2015. '*Paste deposition modelling, deconstructing the additive manufacturing process: Development of novel multi-material tools and techniques for craft practitioners*' PhD Thesis, Brunel University, London

Learning from advancements in additive manufacturing[23, 24, 25] this research builds on experiments with 3D printing a great spectrum of materials such as starch-based[26] and chitosan-based[27] bioplastics, mycelium paste[28], clay[29] and salt[30]. Applied to the construction of medium to large-scale pieces, both in labs as well as on sites, these projects lay a foundation for a new way of fabricating one-of-a-kind pieces with reduced energy consumption and material waste. Interested in material behaviours and adaptations, *Printing with Biofoams* is framed as a collaboration between the human, the material and the technology. It takes into account the unique qualities of each tested material and printing process, leaving room for unexpected outcomes and responding with flexible research directions to form a better understanding of the potential fabrication and application of printed biofoams.

Findings from the material research contribute to further explorations of speculative scenarios for transient dwelling spaces using recyclable, reusable and compostable materials. Supporting symbiogenetic relationship between temporary interventions and permanent environments, the material applications aim to reduce the impact of the construction sector on the environment[31] while simultaneously increasing the accessibility, affordability and diversity of individually tailored private spaces in urban environments. It is important to acknowledge that these conjectures are rooted in a speculative design approach with an intention to explore plausible and possible futures[32] through material research and experimentation.

How can we utilise transient architectures to contribute to the longevity of planet Earth? How can we increase the adaptability and responsiveness of built environments? How can we minimise construction processes to increase resource, energy and time efficiency? How can we minimise material extraction to achieve maximum impact? How can new materialities make our cities more affordable? More accessible? More inclusive? More dynamic?

24 Shi, Yusheng, et al. 2021. Materials for Additive Manufacturing. Elsevier Science, Amsterdam

25 Yuan, Philip F., et al. 2018. Digital Fabrication. Tongji University Press, Shanghai

26 Materiability Research Group 2020. *3D Printing Bioplastics* accessed 18 June 2022, <https://materiability.com/portfolio/3d-printing-bioplastics/>

27 Mogas-Soldevila, Laia, Duro-Royo, Jorge, Oxman, Neri 2015. 'FORM FOLLOWS FLOW: A Material-driven Computational Workflow For Digital Fabrication of Large-Scale Hierarchically Structured Objects' *Acadia – Computational Ecologies: Design in the Anthropocene* 2015 Conference, Ohio. <http://rb.gy/9dtv9>

28 Blast Studio 2022. *Blast Studio* accessed 18 June 2022, <https://www.blast-studio.com/our-innovation>

29 Keep, Jonathan 2020. *A Guide to Clay 3D Printing* accessed 18 June 2022, <http://keep-art.co.uk/Journal/JK_Guide_to_Clay_3D_Printing.pdf>

30 Emerging Objects 2013. *Saltygloo* accessed 23 July 2022, <http://rb.gy/zpe09>

31 ECOS 2020. *From Barrier to Enabler: Towards a greeener EU construction products policy* accessed 18 July 2022, <http://rb.gy/posko>

32 Raby, Fiona and Dunne Anthony, 2013. Speculative Everything: Design, Function and Social Dreaming, MIT Press

Preceding page and above A collection of biofoam samples demonstrates experiments with different formulas to produce a range of biofoam densities, thicknesses, colours and surface finishes

Biofoams

Biofoams are formed by introducing gas into liquid bioplastics through either a chemical or a physical reaction. Throughout this research, bioplastic foundations containing a foaming agent are exposed to circular motions, altering their physical state to produce biofoams in varying densities. Building on projects such as Algae Foam by Bloom[33] increasingly used in the footwear industry, Biofoam packaging by BEWI[34] and BioFoamPearls packaging by Termokomfort Netherland B.V.[35], the intention is to expand the variety of available biofoams and their applications within the limited use of a single biopolymer (gelatin, agar, carrageenan iota or sodium alginate), solvent (water), bioplasticiser (glycerin) and bioadditive (foaming agent). Further minimising the number of required processing and manufacturing stages, the following experiments focus on adapting ratios of individual components and different processing techniques to achieve the most time, resource and energy-efficient production of biofoams in ranging flexibilities, densities and thicknesses.

Initial experiments with cooking biofoams include gelatin, agar-agar, tapioca starch and sodium alginate-based recipes. It was quickly determined that the latter two have a limited range of adaptations with sodium alginate most suitable for very delicate and thin layers of biofoam and starch-based biopolymers performing best in bulky, high-density structures due to their thick and doughy consistency. As a result, gelatin and agar-agar are two primary biopolymers used in experiments throughout the research period.

It is important to note, that from the onset of this research, the intention was to produce algae-based biofoams[36, 37] to avoid contributions to the meat industry, recognised as one of the main contributers to global greenhouse gas emissions.[38] However, the industry's by-product - gelatin was used for initial recipe tests due to its easier processing and

33 Bloom 2016. *Algae Foam* accessed 21 July 2022, <https://www.bloommaterials.com/the-bloom-story/ >

34 BEWI 2021. *BioFoam* accessed 02 July 2022, <https://bewi.com/products/biofoam/ >

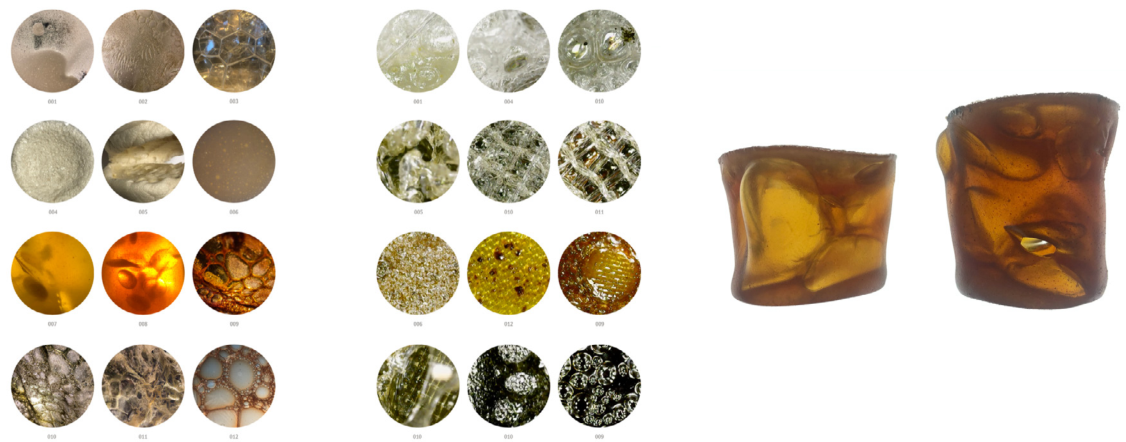
35 Termokomfort Nederland B.V. 2014. *BiofoamPearls* accessed 29 July 2022, <https://www.termokomfort.nl/isolatieparels/biofoampearls >

36 Biorefinery concept

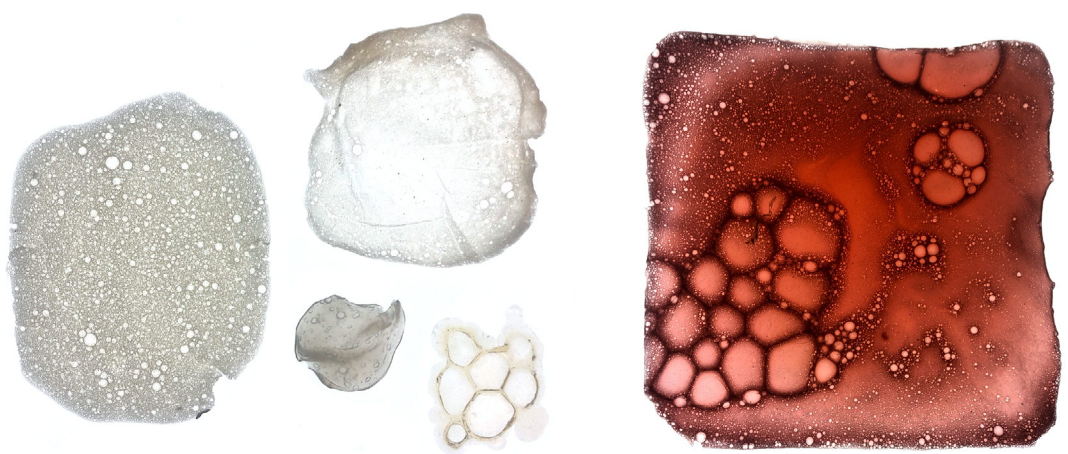
"high-value bioactive compounds produced by microalgae" used in the biofuel industry, including "agars, agarose, alginates, carrageenan"[37] can be utilised in the production of a range of biomaterials, increasing the biofuel industry's cost efficiency as well as contributing to waste reduction and carbon utilisation.

37 Rizwan, Muhammad et al. 2018. 'Exploring the potential of microalgae for new biotechnology applications and beyond: A review.' *Renewable and Sustainable Energy Reviews 92* (2018): 394-404, p.395 <https://www.researchgate.net/publication/325193566_Exploring_the_potential_of_microalgae_for_new_biotechnology_applications_and_beyond_A_review>

38 Xu, Xiaoming, Sharma, Prateek, Shu, Shijie et al. 2021. Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. *Nat Food 2* (2021): 724–732. <https://doi.org/10.1038/s43016-021-00358-x>



Above From micro to macro scale observations of different types of biofoam structures that can be created with a variety of biopolymers including gelatin, agar, tapioca starch and sodium alginate



Above Samples of biofoam surfaces with varying zonal properties created by pouring, casting as well as manually 3D printing biofoams L - R agar, sodium alginate, tapioca starch, gelatin

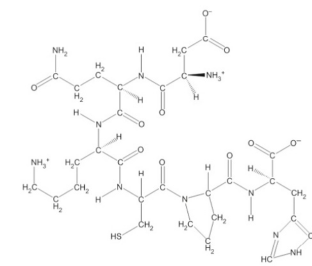
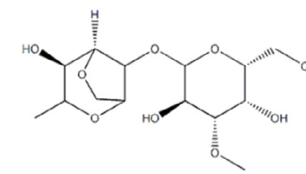
	GELATIN	AGAR
		
Source	Animal bones and skin	Red algae
Type	Protein	Polysacharide
Texture	Smooth, flexible, rigid	Firm, flaky, flexible
Colour	Translucent yellow	Cloudy white
Melting temperature	40°C | 35°C water	85°C | 60°C water
Dissolving time	1 - 2 hours	5 - 6 hours
Setting temperature	18°C - 20°C	32°C - 40°C
Shrinkage	up to 40%	up to 70%
Reusability	Re-melting at 40°C after a few minutes	Re-melting at 60°C after 20 to 60 minutes

Table above Comparison of gelatin and agar material characteristics and processing methods

Above and facing page A series of samples demonstrating experiments with a range of foam-making processes. These include the implementation of the chemical reaction between vinegar and baking soda resulting in uneven, high-density foams as well as more consistent homogeneous samples using castile soap

manipulation (lower melting point, lower setting temperature, longer working time, faster remelting and lower price point) before further adaptations to more environmentally friendly agar-based recipes. As previously mentioned, the recipes were reduced to only four components[39]: biopolymer, solvent, bioplasticiser and foaming agent[41]. Both biopolymers use water as a solvent, glycerin as a plasticiser and Castile soap[42] as a foaming agent. Their similar processing methods and components' ratios allowed close observations and constant comparisons between the visual, odour and tactile qualities of gelatin and agar-based biofoams including their compression, spring back time and distortion.

Agar forms strong, linear bonds which result in a firm, flaky structure, while gelatin is more flexible and bouncy (p.12). A difference can be also observed in the cloudy white colour of agar as opposed to gelatin which is clear with a hint of golden tones. While colour differences are less obvious when the biopolymers are whisked to form a biofoam, the difference in their tactile qualities remains noticeable. Gelatin forms solid structures when cured and therefore requires larger amounts of glycerin to produce a flexible biofoam that quickly bounces back to shape. Agar recipes compared to gelatin require higher amounts of water with a lower amount of glycerin to produce biofoams with similar flexibility and adaptability.

A spectrum of flexibilities, densities and thicknesses can be achieved by primarily controlling the amount of water, glycerin and whisking time. Increasing the amount of glycerin reduces shrinkage during curing, preserving lower-density structures of biofoams as well as increasing the flexibility of the final forms. However, the final form remains tacky and slimy if too much glycerin is used. Therefore, it is important to gradually increase the amounts of individual components in the compound to observe subtle changes in the physical qualities. Increasing the amount of water increases the flow of the biofoam, allowing more complex shapes to be filled and thinner sheets to be produced. Contrary to glycerin, higher amounts of water increase the shrinkage percentage as well as extend the curing time. Therefore, it is important to balance these two components depending on the chosen application process as well as the required consistency. The amount of foaming agent is consistent throughout at a ratio of 1:50 with the remaining liquid components.

39 Limited use of four components for the production of biofoams was inspired by Benyus's observation of the efficiency of natural processes which utilise a limited number of non-toxic elements to build complex structures while the construction industry utilises a majority of the periodic table.[40] Introducing limitations to the material resources, processes and technologies used throughout this research presents a challenge to conduct in-depth studies of biomaterials to understand their full potential to perform in diverse environments and under varying constraints with minimal human input

40 Benyus, Janine, M. 1997. Biomimicry: Innovation Inspired by Nature. Morrow

41 Foaming agent research involved experiments with a variety of natural foaming agents including vinegar and baking soda, acetic acid with calcium carbonate as well as a range of plant-based soaps. Combination of castile soap and whisking has proven to be the most efficient process for creating homogeneous biofoams in a variety of densities and flexibilities

42 Castile soap is a plant-based foaming agent traditionally made of olive oil, however, recent adaptations also use coconut, castor or hemp oils

Above Colour-coded samples use natural pigments to visually emphasises gradual increase in the biomaterial's flexibilities

Sample recipe testing process:

TASK:

Experimentations making a topography with gelatin-based biofoam with increasing flexibilities throughout. Using pouring technique with moulds and sealing afterwards.

RECIPE:

500ml water, 180g gelatin, 100ml glycerin (30ml each sample)

NOTES:

each sample with 30ml base mix + 0.3ml glycerin each time

0-4.5ml of extra glycerin

The higher the volume of glycerin the faster the solution sets - don't over whisk the foam as it will quickly become solid and form lumps throughout the material

If thickened reheat the foam in a pot and pour again

The volume of the foam doesn't seem to change much with the changing ratio - the volume decreases only when shorter time of whisking is required before the foam starts thickening up. Shorter whisking time also increases foam and liquid separation. Changes in volume are noticeable once the material is cured - the higher the amount of glycerin the smaller the shrinkage.

QUESTIONS:

How can I increase control over the flow of the material? How can I create more accurate forms? What is the maximum number of layers achievable with gelatin-based biofoams? How many different densities can be achieved?

Step 1 Pour cold water in the pot

Step 2 Add agar powder and stir thoroughly until it dissolves

Step 3 Heat the mix for 2 min on power 2 of an induction plate before adding glycerin

Step 4 Stir continuously on power 3 until the mixture starts to boil

Step 5 Whisk on high speed until homogeneous foam is formed

Step 6 Fill up a large syringe with the biofoam while still hot

TASK:

Experimentations making a topography with agar-based biofoam with increasing flexibilities throughout. Using pouring technique with moulds and sealing afterwards.

RECIPE

500ml water, 36g agar, 70g glycerin (30ml each sample)

NOTES:

each sample with 30ml base mix + 0.3ml glycerin each time

0-4.5ml of extra glycerin

Stop heating the solution as soon as the mix starts to thicken (reheating is possible afterwards). Keeping the pot closed and on a warm surface prevents the mix from setting.

Agar based biofoam doesn't increase much in volume when whisked compared to gelatin-based biofoam due to its thicker base solution - add more foaming agent to create lower density biofoams. The biofoam sets very quickly and it is important to be careful not to overwhisk the mix as it will set and create lumps.

QUESTION:

Will regulating the volume of agar in the mix also effect the density of the foam? How can I easily edit the recipes to gradually change flexibilities I am printing with? How can I increasing the printing life of agar-based biofoams?

Above Sample of a gelatin-based biofoam surface with varying zonal properties

Scale 120 x 120 x 35mm

Casting Biofoams

Injection moulding is used for manufacturing standardised forms by pouring liquid materials into moulds before setting to a solid state. When it comes to material experimentations and developments, this process allows quick and easy production of samples, clearly highlighting differences in individual material alterations. This includes unique textures, flexibilities, colours as well as curing times, distortions and inconsistencies in the form.

Hence 3D printed PLA moulds 120 x 120 x 35 mm are used for quick prototyping of biofoam surfaces with varying zonal properties. Inspired by the cell structures of the human skin, the form is divided into multiple individual units, allowing specific variations of recipes to be applied depending on the required surface performance. Held together on a base of agar, gelatin or recycled cotton, diverse topologies are created with unit sizes ranging between 5 - 60 x 5 - 50 x 35 mm (p.19). These experiments show how the shrinkage during the curing process varies depending on the amount of plasticiser in the individual compounds. Harder and denser biofoam zones shrink by up to 70% while softer, more flexible and lower-density biofoams shrink by approximately 20%. Consequently, the scale of the mould design needs to take into account the predicted shrinkage of each biofoam variation to prevent CAD model distortions throughout a heterogeneous biofoam surface. Zones that are expected to have a harder, denser consistency will benefit from larger moulds, giving them more room for shrinkage, while lower-density foams can use moulds with only a 20% increase in the desired size. Closer observations and calculations are necessary to determine the exact shrinkage percentage for each type of biofoam.

Using a flexible base enables adaptation during the curing process without causing unpredictable distortions in the surface.

Above Fast setting time surface height inconsistencies

Above Uneven air bubble distribution surface texture inconsistencies

Above Varied shrinkage percentage form distortion

Above Foam separation flexibility inconsistencies

On the other hand, a fixed solid base such as a sheet of recycled cotton preserves the original shape, size and position of the base of each unit. However, the use of a solid base often leads to noticeable form distortions with a higher percentage of shrinkage occurring in the unit height. When using agar or gelatin-based sheets, it is important to make sure they are fully cured before applying the units, as they also shrink and deform if not held in place by a frame.

Further form disruptions caused by the separation of foam and liquid during the setting period can be seen as a contribution to the expansion of tactile qualities throughout the biofoam surface. These observations open up a new area of possibilities for layering and interlacing various biofoam consistencies to achieve a complex surface, tailored to specific physical requirements.

Can a low-density biofoam be coated with a thin layer of biofoil? Can a bioresin unit be overlayed with a low-density biofoam? Can they be combined to create a smooth gradient? Would this work vertically as well as horizontally?

While there are multiple challenges when working with injection moulding including density inconsistencies, foam-liquid separation and shrinkage, this process allows fast and efficient prototyping of small-scale biofoam surfaces. As expected, some of the unpredictable outcomes further expand the spectrum of this research, proposing new approaches, methodologies as well as potential applications of biofoam structures. Observations from this stage are further applied to adaptations of recipes and handling of biofoams in additive manufacturing.

Above   Initial experiments with agar-based biofoams reveal homogeneous surfaces with high flexibility and adaptability
Agar Biofoam: Water 88.3%, Agar 3.5%, Glycerin 6.8%, Foaming agent 1.5%

Following page L   Detail of a heterogeneous agar-based biofoam surface with high-density units in the front

Scale 120 x 120 x 35 mm

Above   Initial experiments with gelatin-based biofoams reveal a clear separation of soft, flexible biofoam and hard, sturdy bioplastic base
Gelatin Biofoam: Water 79%, Gelatine 7.5%, Glycerin 12%, Foaming Agent 1.5%

Following page R   Detail of a heterogeneous gelatin-based biofoam surface with vertical density separation in the front

Scale 120 x 120 x 35 mm


01
02
03
04
05
06
07
08
09
10
11
12
13
14
15
16
17
18

Printing Biofoams

3D printing is a single-step additive manufacturing process that allows the layered extrusion of materials to form three-dimensional objects. The biggest benefits of utilising this fabrication process include time and cost efficiency, flexibility, accessibility and adaptability, contributing to the overall sustainability of biofoam production. Based on CAD models, print scales can vary anywhere from micro-scale components[43] to macro-scale 3D printed construction of houses[44]. Whilst Eric Klarenbeek[45] facilitates a collaboration between 3D printing machinery and nature to create new materials suitable for a variety of products such the Mycelium Chair, Synthesis Design and Architecture paired up with Stratasys to create Durotaxis Chair[46] which utilises multi-material printing to create a gradient of material qualities and performances. The following research focuses on small to medium-scale models, drawing inspiration from projects which attempt to achieve responsive, multi-material structures.

MANUAL EXTRUSION

Initial experiments with biofoam printing are carried out using a manual extruder such as a syringe or a caulking gun. The intention is to gain a better understanding of the flow of gelatin and agar-based biofoams, their ability to form layers, different densities as well as their maximum print heights, setting time and curing conditions. Simple patterns of lines, circles, curves and topographies are tested to enable clear observations of unique material behaviours (p.30).

The gelatin recipe used for the first experiments contains 240ml water, 62g gelatin, 34ml glycerin and 5ml foaming agent. The solution is very thin as a result of increasing the

Preceding page Results of first experiments with printing medium-density gelatin-based biofoam using Delta Wasp's Liquid Deposition Modeling technology

Scale 90 x 90 x 2 mm

43 Sabin, Jenny et al. 2019. 'POLYBRICK 2.0: Bio-Integrative Load Bearing Structures.' *ACADIA 2019 (Ubiquity and Autonomy) 2019: 222-233.*

44 WASP & Mario Cucinella Architects 2021. *TECLA* accessed 03 July 2022, <https://www.3dwasp.com/en/3d-printed-house-tecla/>

45 Klarenbeek & Dros - Designers of the Unusual 2011. *KROWN.bio* accessed 03 July 2022, <http://www.krown-design.com/>

46 Yuan, Philip, F. et al. 2018. Digital Fabrication, Tongji University Press

Facing page Details of first manually extruded gelatin-based biofoams used to study the flow of biofoams, their adhesion and setting time. Line width 2mm

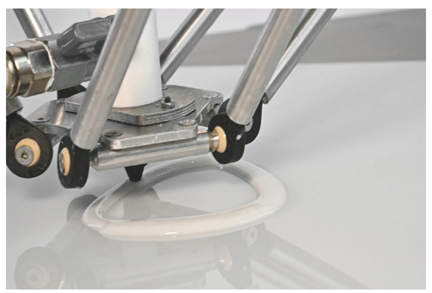
What is the difference in gelatin and agar biofoams' consistencies? How many layers can be achieved? To what extent can the shape be controlled? How precise can the print be? What size nozzle is most effective? What is the print life of each biofoam variant? What are the optimal environmental conditions for printing biofoams?

amount of glycerin in the recipe. To avoid additional cooking time the amount of water is reduced to 200ml, forming a thicker bioplastic foundation. Allowing the biofoam to rest at room temperature for approximately two minutes before printing with occasional stirring also increases its thickness and stability. If separation of liquid and foam starts occurring, a thin bottom layer can be extruded on the side before carrying on with printing the model. The waste material can be recycled for the next filament without affecting its printing quality. Using a handheld mixer helps form an even and smooth biofoam filament. Additional cooking with slow, continuous stirring removes larger bubbles, resulting in a homogeneous biofoam filament.

The agar recipe used for the first experiments contains 280ml water, 15g agar, 13g glycerin and 10ml foaming agent. The solution is smooth, evenly spread and easy to apply. There is a noticeable increase in precision and control when working with agar biofoam as opposed to gelatin. Due to the quick setting time of agar at higher temperatures, detailed and delicate forms can be achieved during its thicker state. However, when it comes to curing, the shrinkage distortions are much more noticeable. Therefore, it has been concluded that printing on a larger scale as well as increasing the amount of glycerin is necessary to prevent distortions of the designed pattern. Furthermore, reheating agar-based biofoams takes a significantly longer time to completely dissolve and remove all lumps and material inconsistencies.

Following initial evaluations of both gelatin and agar-based biofoams, honey is added to gelatin recipes to increase the smoothness and flexibility of the biofoam. The recipe consists of 200ml water, 150ml gelatin, 100ml glycerin, 50ml honey, and 10ml foaming agent. While this additive helps to create a much more homogeneous and flexible biofoam with a quicker setting time, it also increases the stickiness of the surface, making it more prone to collecting dirt, attracting insects and cultivating other microorganisms. To further prevent the spread of mould, especially in agar-based biofoams, all working areas and tools need to be constantly disinfected and samples cured in either cool, dry environments with a fairly consistent temperature or at 40-50ºC in the oven.

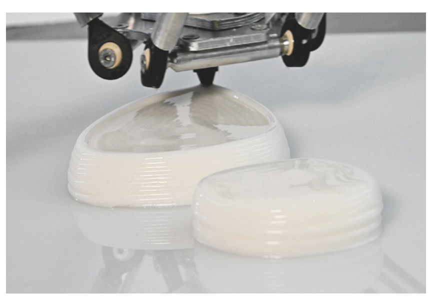
Overall, these manual extrusion tests confirm previous experiment-based assumptions that agar biofoams are more suitable for high-quality 3D printing due to their thicker cosistency and quicker setting time. However, the processing of agar biopolymer requires a much higher temperature to preserve the printing consistency as well as longer reheating times when recycled. This suggests that gelatin-based biofoams are more suitable for quick prototypes with their easy and quick recycling processes before moving on to final agar-based biofoam prints.



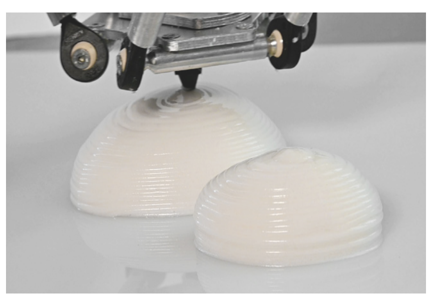
Step 1 Perimeter

Step 2 Base

Step 3 Third-way through



Step 4 Mid-way through



Step 5 Top tangent

Step 6 Final form

AUTOMATED EXTRUSION

When progressing to automated extrusion, Liquid Deposition Modeling (LDM) technology developed by the Italian company Delta Wasp[47] is used to print with more precision and control (p.31). Since this setting is intended primarily for printing with thicker materials such as clay[48], the system requires multiple adaptations before it is suitable for printing lower-density materials such as biofoam. Throughout the experiments, it has become clear that multiple factors affect the quality of biofoam prints. From the shape of the extruder, the size of the nozzle to the temperature of the environment and the height and width of individual layers. The setting time of biofoams fluctuates and so the required printing conditions may change throughout the process. As some factors can't be altered during printing, it is important to pay close attention to the pressure and speed of printing to quickly respond to the material's changing requirements.

Extruder

The first adaptation focuses on redesigning the extruder. The original extruder uses a screw to feed the thick filament to the nozzle with an opening to release unwanted air bubbles. Both of these features are causing disruptions to the biofoams' flow and consistency hence a simple, enclosed PLA extruder with a conical cavity is 3D printed. Multiple adaptations are gradually tested in collaboration with Chris Busch, finally adding a manual valve and a small opening for cleaning (p.33).

Direct Drive

The original LDM setup using a combination of pneumatic and screw extruders is used during initial tests (p.27), however, this set-up is too powerful for biofoams and causes over-extrusion followed by extreme inconsistencies in prints. The most successful prints are produced with the residual pressure after turning off the pressure drive

47 3D Printing Media Network 2021. *Liquid Deposition Modeling (LDM)* accessed 21 July 2022, <http://rb.gy/bdg2q>

48 Mario Cucinella Architects 2021. *The first eco-sustainable housing model 3D printed from raw earth* accessed 21 July 2022, <http://rb.gy/oo8nh >

Facing page Individual stages of printing biofoam units capture the layer adhesion and form setting throughout the process

[Video link]

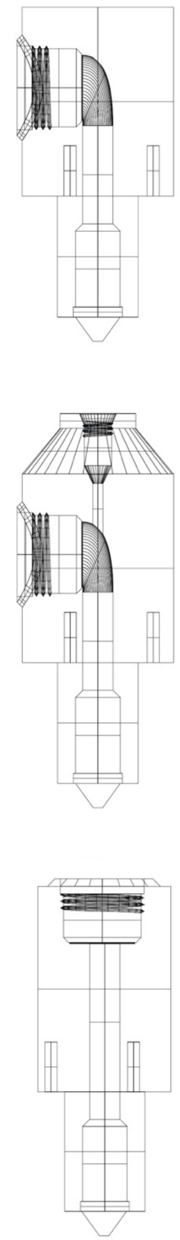
and so transitioning to a direct drive provides much finer pressure control and enables immediate adjustments to the flow of the filament. The construction involves an Arduino, a stepper motor, railings and several 3D-printed fastenings to hold the filament tank in position (p.34). A potentiometer enables control over the spinning speed of the motor, directly affecting the speed and direction of the plunger. As a result, the extrusion speed can be adjusted throughout the printing process, responding to print inconsistencies or changing material behaviour.

Material Adaptation

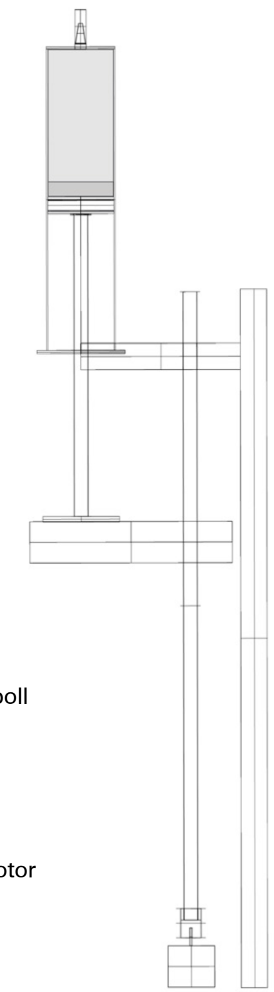
As previously experienced with injection moulding and manual extrusion, separation of biofoam and liquid bioplastic gradually occurs in the filament tank, leading to density gradients in the final prints. The recipes are modified to create thicker, more homogeneous filaments in order to gain more control over the print quality. The content of water needs to be reduced to avoid the spreading of layers, resulting in thicker bioplastic foundations. The whisking time is increased to 3 minutes to create smooth, homogeneous biofoams.

Nozzle Size

Tests are carried out using a range of nozzle sizes from 0.8mm to 3mm. While successful prints are achieved with all sizes, 2mm and 3mm nozzles prove to be most suitable for printing medium-scale, solid objects. The required extrusion pressure decreases in line with decreasing nozzle sizes, meaning the smaller the nozzle the slower the printing process which can cause issues with premature material setting. To achieve accuracy in delicate and detailed prints, it is important to use low printing speed and low pressure to prevent material build-up and subsequently printing inconsistencies. This places further importance on creating an optimal environment to extend the printing life of biofoams.



Above Illustrations of a number of extruder adaptations in collaboration with Chris Busch to prevent material cooling and blockages



Above Illustration of the direct drive components adapted in collaboration with Arthur Wilson to allow fine control over the material's flow-rate

Layer Height

The optimal layer height changes depending on the density of biofoam. When working with a 3mm nozzle the height ranges from 2mm to 4.5mm. Lower layer height settings are suitable for lower-density biofoams as the low position of the nozzle helps direct the material to the desired position and prevent it from rapidly spreading. With higher-density foams, this setup causes blockages in the nozzle as the material is too thick to be spread out in smooth layers. Therefore raising the nozzle to 4 - 4.5mm allows a smooth flow of the filament without direct contact with already printed layers. Due to the thicker consistency of high-density biofoams, the direction of the flow is accurate and doesn't require force to prevent leakage. If the nozzle is set too high, the filament starts forming swirly layers that cause further inconsistencies in the print if such effect is not desired.

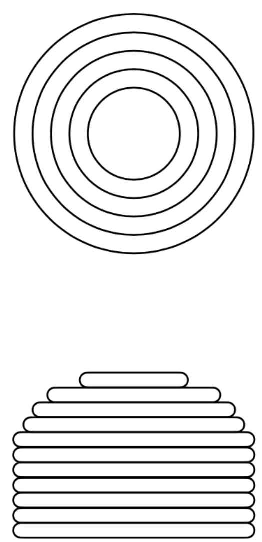
Temperature

While gelatin-based biofoams have a printing life of approximately 30 minutes at room temperature due to the slow setting time of gelatin, agar cures much quicker causing blockages in the nozzle as well as the printing tube. Increased pressure used to remove lumps in the filament only leads to material build-up and further blockages. Therefore, heating elements are introduced in the area of the filament tank[49] and the tube, keeping the biofoams above their setting temperature. Preheating the nozzle area before printing has also proved to increase the flow of the material and prevent blockages caused by material cooling in the metal environment of the nozzle. Lastly, scaling up to a 500ml syringe allows a larger amount of material to be stored, further slowing down the cooling process in the filament tank.

Following various experiments, adaptations and adjustments of the LDM extrusion, it can be concluded that it is possible to achieve accurate prints of biofoams in varying forms, scales, thicknesses as well as densities and flexibilities. There is a potential to form complex biofoam structures with varying zonal properties, which can be further expanded using a large 3D printer or a robotic arm. In terms of material quality, the inconsistencies are reduced to a minimum with the increased control and precision of automated manufacturing, however, further research is necessary to increase the control over gradient material applications and accurate shrinkage. By allowing quick adaptations of printing settings, this system can respond to changing behaviours of the materials, form requirements and environmental conditions. This further emphasises this project's core intention to nurture collaboration between the human, the material and the technology.

49 Schunemann, Esteban 2015. '*Paste deposition modelling, deconstructing the additive manufacturing process: Development of novel multi-material tools and techniques for craft practitioners*' PhD Thesis, Brunel University, London p. 176 - 180

Preceding page Adaptations of the extruder form and direct drive are tested to allow a smooth flow of biofoams, reducing the compression and therefore density distortions of the material during printing



Above CAD model slice of a single unit using Cura

Nozzle 1mm **Speed | flow-rate***

Line Width / Layer Height	2	2.5	3	3.5
1.5	35 | 0.844	35 | 1.055	28 | 1.055	21 | 1.055
0.5	35 | 0.703	31.5 | 0.703	31.5 | 0.703	30 | 0.703

Nozzle 2mm **Speed | flow-rate***

Line Width / Layer Height	2	4	4.5	5
2	35 | 0.3	35 | 0.37	24.5 | 0.4	21 | 0.4
1	35 | 0.2	35 | 0.241	35 | 0.3	31.5 | 0.4

Nozzle 3mm **Speed | flow-rate***

Line Width / Layer Height	4	5	6	7
3	35 | 0.3	35 | 0.3	42 | 0.37	35 | 0.4
1	35 | 0.3	35 | 0.3	24.5 | 0.343	21 | 0.37

Table above Notes on the relationship between speed and flow-rate when printing with a range of nozzle sizes

* Printing speed (mm/s) and volumetric material flow-rate (ml/s) may vary depending on the biofoam density as well as the temperature of the environment and the detail of the design. In addition, required flow-rate might decrease with increasing layers

01
02
03

Above Initial experiments printing gelatin-based biofoams reveal inconsistencies in density and flow caused by increasing pressure in the filament tank and separation of the biomaterial's foam and liquid parts. Further observations and experimentations are required in order to incorporate vertical gradients of biofoams in a more controlled manner

Above 3D printing high-density gelatin-based biofoam with reduced content of water increases the material's homogeneity. This enables more consistent behaviour of the material in combination with refined printing settings

Above Freshly printed medium-density, high-flexibility agar-based biofoam units are very delicate and bouncy. Compression is noticeable in the lower quarter, however, the overall surface is even and smooth

Scale 100 x 61 x 30 mm

Preceding page and above Freshly printed high-density, low-flexibility agar-based biofoam units are firm and sturdy. Compression is only noticeable in the base layers, however, the overall surface is even and smooth with only subtle layer inconsistencies

Scale 58 x 42 x 25 mm

Above An assembly of a range of agar-based biofoam units forms a density and flexibility surface gradient

Above Detail of a cured agar-based biofoam unit shows refined layers with a decrease in form inconsistencies due to the biomaterial's shrinkage during the curing process

Above Interaction with a range of agar-based biofoam units shows the difference in the densities, flexibilities and thicknesses of the material, achieved through a range of material formulas as well as 3D printing settings

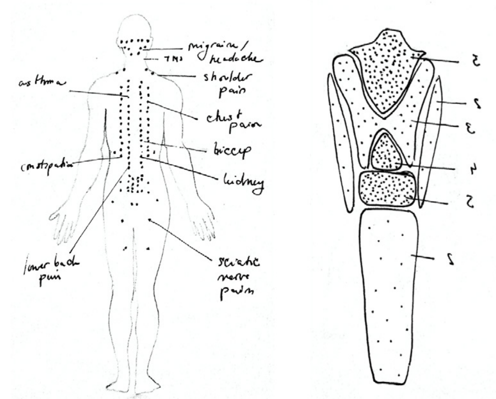
Applications of Printed Biofoams

Applications of printed biofoams are considered through speculative designs rooted in this biomaterial research project. Simultaneously explored throughout the research, the primary focus is on the role of recyclable, reusable and compostable material solutions in temporary habitats. The experimental implementation of printed biofoams in the context of private spaces explores the potential of their materialities to transform spaces, challenge our perceptions and nurture intimate relationships with built environments[50]. *Printing with Biofoams* seeks to apply biomaterial research findings to reimagine the physical and psychological role of dwelling spaces in urban environments. Reimage the way we occupy them, navigate them and connect with them[51], blurring the boundaries between the built and natural environments.

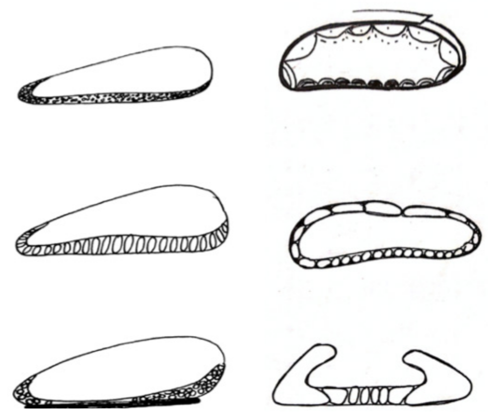
"We imagine the building and our spatial environment as a second skin, an extension or projection of our body and our psychology; we wear spaces and morphology like clothing or a membrane, an interface or prosthesis, physically and psychically, and indeed socially and collectively." [52]

Jon Goodbun, 2011

This stage of the project lets the novel biomaterial's unique qualities and its fabrication process reveal new concepts and forms of dwelling structures. The material's responsive behaviour naturally draws a relationship with adaptable, flexible and mobile housing structures, explored in the 1960s through projects such as Living Pod (David Greene,1966) [53], Cushicle (1964) and Suitaloon (Michael Webb,1967)[54] or more recently with adaptable living units such as the Ecocapsule[55] and coodo[56]. Taking into account both the physical and

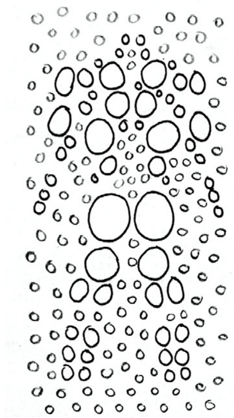


Above Categorising body pressure points

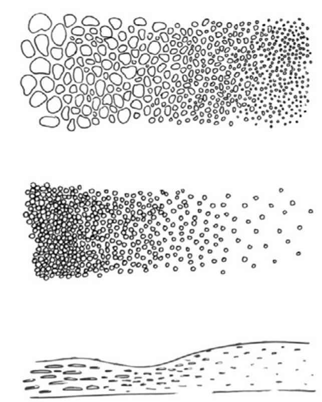


Above Cocoon-like unit structure intends to encapsulate the human body

50 Keedwell, Paul 2017. Headspace: The Psychology of City Living. Aurum Press Ltd., United Kingdom



Above Subdivision of individual zones



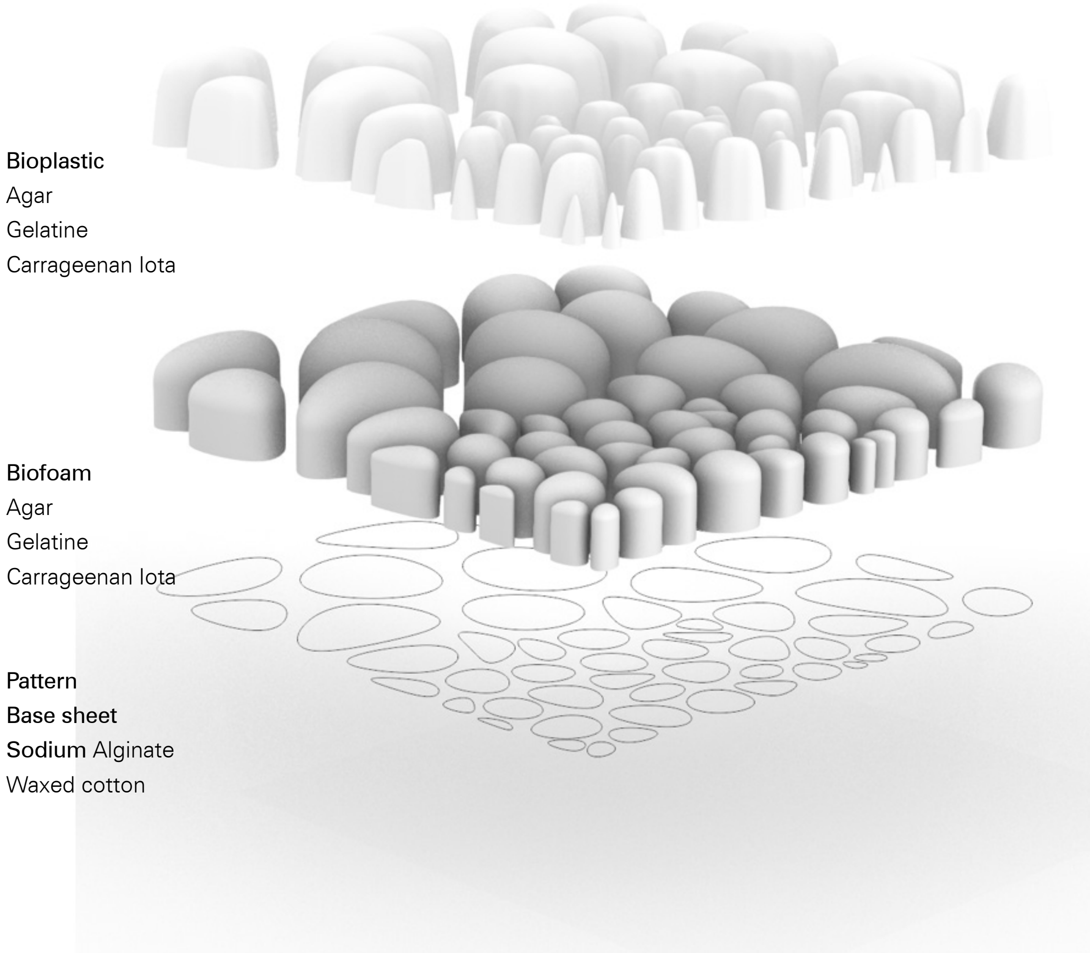
Above Different ways of achieving density gradients through air bubble distributions

51 Hesselgren, Sven 1977. Man's perception of man-made environment: An architectural theory. John Wiley & Sons Inc, New York

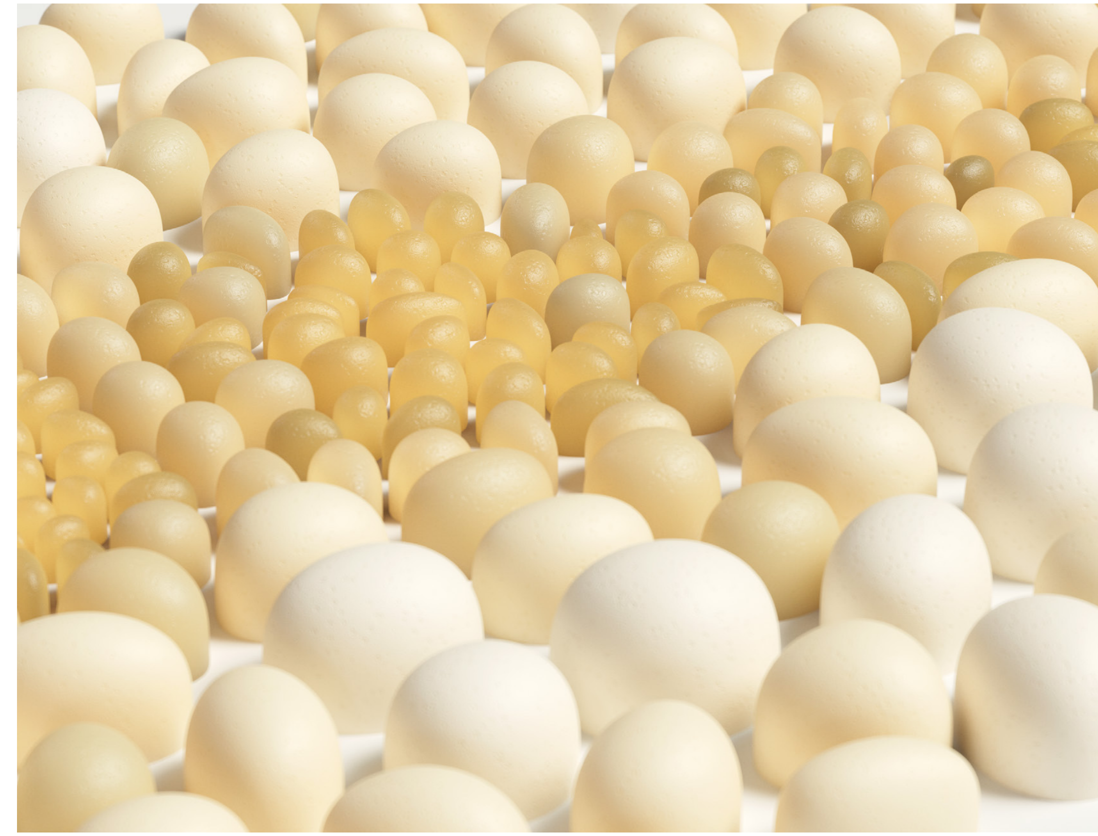
psychological preferences of individual projects, *Printing with Biofoams* aims to create an environment that is tailored to each body individually, adapting and responding to its unique features and behaviours as well as the constantly changing external conditions. It learns from natural structures such as a cocoon or a womb and the behaviours of our skin, to design a non-invasive and low-maintenance living unit. An optimal living environment which seamlessly morphs around the body to merge with its constantly changing state of being.

A prototype of an agar-based biofoam surface is constructed with specifically designed zonal properties including rigidity, flexibility, density and thickness (p.53). Collecting information about individual pressure zones of the human body, the design utilises a similar unit system as seen during injection moulding tests (cell structures, p.4). The whole sheet measuring 800 x 1200 x 35mm, is divided into 358 individual cells of varying sizes and 5 grades of agar-based biofoams are arranged to achieve the required material performance. Areas with little to no contact with the body consist of low-density biofoam units between 80 -100 x 60 - 90 x 35 mm to enable flexible wrapping around the body. The density gradually increases as higher pressure areas are reached with unit sizes decreasing to enable more control over the physical qualities and performance of the material. The smallest unit sizes are between 10 - 20 x 8 -20 x 20 mm. Overall, the whole structure is made of approximately 14 600 ml of agar-based biofoams and took 12 hours of printing.

Due to the restricted printing area, the units are printed in small groups depending on their biofoam grade. Afterwards, they are applied to a large agar-based sheet using a thin agar biofoil solution as an adhesive. Custom-made direct-drive and extruder are used for the whole production, with nozzle size varying between 2mm and 3mm depending on the size of the units. Taking into account the shrinkage of agar-based biofoams, the size of the larger units was increased by 20% while the smaller units were increased by as much as 60% to match the original CAD pattern. While the low-density

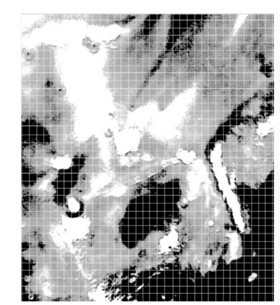


Above Individual layers of a single biofoam structure. Sodium Alginate or waxed cotton base create a waterproof layer that protects the soluble biofoam structure from humidity and temperature changes of the permanent environment. Optional bioplastic coating can be used to even out surface inconsistencies as well as expand the visual qualities of the biofoam surface

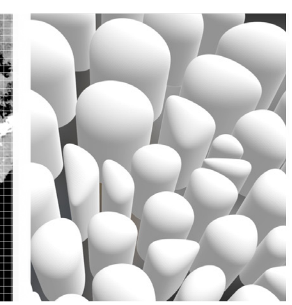


Above Parametrisation enables easy manipulation of the pattern to meet individual requirements of the body. Render demonstrates a potential arrangement of different biofoam grades to achieve the desired performance of the whole surface. The higher the pressure the smaller the units to allow more control over the material behaviour

Right Body pressure zone scans provide accurate visualisations of the unique qualities of individual bodies which inform the biofoam units' subdivision and arrangement. Biofoam grades are then assigned to the 3D models based on unit position, size and performance



Pressure zones mapping



Parametric design

Biofoam topography

units cured within the expected size and shape distortion, the highest-density units shrunk by up to 70% leading to noticeable size and shape distortions. This can be compensated by introducing more high-density units in the affected areas.

Grade	Water	Agar	Glycerol	F. Agent
1	87.5%	3.4%	6.5%	2.6%
2	88.7%	3.5%	5.6%	2.2%
3	89.8%	3.5%	4.5%	2.2%
4	91.2%	3.6%	3.4%	1.8%
5	93.7%	3.7%	1.4%	1.2%

Above 5 grades of agar-based biofoam

Glycerin amounts are gradually increased to provide a gradient of material flexibilities while the foaming agent is adjusted in correlation with the whisking time to control the material density.

Following tests with the agar-based biofoam surface, it can be concluded that medium to large-scale units, positioned closer together will increase the comfort of the printed environment without compromising its adaptability to the unique requirements of the human body. Furthermore, layering different biofoam grades will introduce more complexity to the tactile qualities of the material allowing a higher degree of control and precision over its final performance. In terms of durability, tests are carried out throughout the process to assess the material's ability to withstand the weight of the human body. No permanent distortions have yet been observed on the units, however, tests over a longer period are required to determine the durability of the structure when exposed to regular physical interactions. Producing a full-scale prototype will provide further opportunities for assessing the effectiveness of the proposed form, structure as well as material application.

The agar-based biofoam prototype is only a starting point for further explorations and developments of flexible and responsive biofoam environments. Combining locally sourced, regenerative materials with the efficiency and accessibility of 3D printing technologies, concepts of flexible, affordable and localised fabrications[57] are envisioned. Intrigued by the future of temporary settlements and concepts of urban nomads, this research looks for ways of facilitating and encouraging unconfined living without leaving a permanent mark on the environment. It seeks to provide accessible and affordable tailoring of private spaces through the use of recyclable, reusable and compostable materials and modern construction 3D printing technologies. It imagines temporary structures growing and living in symbiosis with already existing permanent sites, providing opportunities for non-invasive, non-toxic adaptations of their forms and functions. Drawing from natural systems and structures, this research attempts to maximise local material sourcing, energy efficiency, and symbiogenetic relationships between humans and the natural environment.

52 Goodbun, Jon 2011. *The architecture of the extended mind: towards a critical urban ecology.* Ph.D. p192, University of Westminster

53 The Funabulist 2011. *# GREAT SPECULATIONS /// LIVING POD BY DAVID GREENE* accessed 02 July 2022, <https://thefunambulist.net/editorials/great-speculations-living-pod-by-david-greene>

54 Architecture Without Architecture 2022. *ARCHIGRAM THE CUSHICLE AND SUITALOON* accessed 02 July 2022, <http://architecturewithoutarchitecture.blogspot.com/p/cushicle-and-suitaloon-were-conceptual.html>

55 Ecocapsule 2022. *About* accessed 02 July 2022, <https://www.ecocapsule.sk/#about>

56 LTG Lofts 2022. *About* accessed 02 June 2022, <https://loftstogo.com/about/>

57 Localised fabrication
The benefit of tested biofoam recipes is that they are not dependent on external factories for recycling or remodeling. All of these compounds can be simply remelted, adapted and reformed with basic household equipment. Individual units allow clear separation to preserve the physical qualities of each agar-based biofoam grade during recycling. In case of larger structures or no longer needed units, smaller temporary factories can be located in cities to aid local communities with the production, maintenance and recycling of biofoam structures

Left and facing page The first prototype of a biofoam surface demonstrates the material's spectrum of physical properties. Responsive and adaptable to the individual's unique requirements, it seamlessly morphs around and merges with the body. This prototype was designed specifically for Virginia Binsch, captured in the image

Scale 800 x 1200 x 35mm

Above and right Detail of individual unit arrangements show high concentration of smaller units around high-pressure zones while larger, softer units are located in the outer areas of the structure. This enables a variety of manipulations from an enclosed, cocoon-like unit to an open mat acting as a second skin to the body

Model: Virginia Binsch

Conclusion

Learning from natural systems, material sciences and digital fabrication technologies, *Printing with Biofoams* intends to develop a range of printable biomaterials utilising an adaptable manufacturing system. Addressing the environmental impact of material extraction, production as well as construction and recycling methods, this non-invasive, flexible system responds to and adapts to the unique physical and psychological requirements of individual projects, reducing the negative impact of standardised material fabrications and applications. It attempts to join a vast spectrum of current design speculations, spatial explorations and material experimentations that seek to improve our living conditions[58, 59], reconnect us with the natural web of life[60] and expand our experiences of surrounding environments[61, 62]. Inspired by revolutionary projects of multidisciplinary studios including Blast Studio, EcoLogic Studio, Exploration Architecture, LabStudio, Oxman and Terreform ONE, *Printing with Biofoams* investigates the potential impact of biomaterials in the context of temporary urban architectures, exploring both the tangible as well as intangible shifts in the role of dwelling spaces.

Various tests are carried out to observe the range of physical qualities of the most commonly available biopolymers - gelatin, agar, carrageenan iota, sodium alginate and tapioca starch. The latter two proved to have limited adaptability, therefore being unsuitable for this research. Gelatin and agar, on the other hand, are the most versatile, easily manipulated and adaptable biopolymers in the production of biofoams with similar physical properties, manufacturing and recycling processes. As previously noted, gelatin-based biofoams are used to test new ratios and processing methods due to the material's longer manipulation time and faster recycling. Findings from initial tests are further adapted and refined using agar to produce larger biofoam samples in varying densities, flexibilities, thicknesses and forms.

58 Pasquero, Claudia and Poletto, Marco 2020. 'Air-purifying playground designed in Warsaw' *Icon* (2021) accessed 6 September 2021 <https://www.iconeye.com/design/air-purifying-playground-airbubble-warsaw-ecologicstudio>

59 Pawlyn, Michael 2010. Biomimicry in Architecture, Routledge

60 TERREFORM ONE 2016. *Urban Farm Pod with Agronomy* accessed 02 July 2022, <https://www.terreform.org/plug-in-ecology>

61 Saraceno, Tomas 2022. *Cloud Cities* accessed 02 July 2022, <https://studiotomassaraceno.org/>

62 Cress, Kevan and Boll, Timothy 2023. Living Architecture Systems Description. Riverside Architectural Press

Successful prints are achieved with both gelatin and agar-based biofoams with minimal adaptations to the LDM 3D printing system. Control over the speed, pressure and scale of the filament extrusion allows further manipulation of the printed material. Overall, the system can be adapted to meet unique requirements of individual projects, responding to specifically designed zonal properties with precision and minimal material waste production. The consistent use of 4 components - gelatin/agar, water, glycerin and foaming agent means that different biofoam iterations can be recycled individually to preserve the original ratios therefore material quality or combined to produce a hybrid material.

The main issues encountered throughout the experimentations are the separation of biofoam from liquid bioplastic and notable shrinkage in the cured forms. However, both of these can be reduced by further adaptation of extrusion pressure and CAD file settings. It must be noted that while these distortions were unexpected, they provide valuable information about the wide range of biofoam behaviours. These findings can be implemented to advance the complexity of designs in the form of vertical density gradients and controlled zonal morphing gradually revealed through the curing process.

With further refinement of the print quality, probable future applications of printed biofoams include interior surfaces and furniture, fashion garments as well as customised protection wear. Introducing more bioadditives such as conductive ink, luminescent pigments or natural dies can expand the range of biofoam qualities to increase their value in the world of interactive design, performance arts and set design[63]. Biofoams are infinitely recyclable, making the material ideal for prototypes and temporary structures with the potential for further material adaptations and new applications. Despite the potential use of biofoams in a range of already available products, this research is interested in their potential to reimagine the concept of dwelling spaces. A full-scale biofoam topography with varying zonal properties is compiled as the first physical prototype for such speculative scenarios

63 Vasquez, Lazaro et al. 2022. 'Exploring Biofoam as a Material for Tangible Interaction.' *DIS '22, June 13–17,* 2022, Virtual Event, Australia

marking a starting point for a series of experimentations rethinking the current physical construction and the psychological connection we form with our personal environments. On one hand, it demonstrates the flexibility of the production system and proves its suitability for the manufacturing of site-specific biofoam structures in a variety of scales, densities, flexibilities and thicknesses. Adaptable to different machines and environmental conditions, this system opens up new possibilities for the production of flexible temporary structures built directly on-site using large-scale printers or robotic arms. On the other hand, this research encourages conversations and further speculations to reimagine the way we perceive, understand and connect with built environments without leaving a permanent mark on the natural environment. The vision is best described by environmental activists, Nancy and Jack Todd, in 1984 -

"*in the evolving synthesis of biology and architecture a neighbourhood could begin to function in a manner analogous to an organism. On the proposed block or neighbourhood scale, parts become symbiotic to the whole and the basic social and physical functions work together. The workings are felt and understood by residents, who live with and operate the components*"[64].

64 Todd, Nancyand and Todd, Jack, 1982. Bioshelters, Ocean Arks, City Farming: Ecology as the basis of design. Sierra Club p. 116

Afterword

This folio is only a fraction of ongoing research, experimentations and collaborations, both human and non-human, that reimage the world around us in order to contribute to a brighter future for planet Earth.

How can we build environments that feel like an extension of physical and psychological self? Environments that listen to, learn from and respond to their occupants? How can we build personal spaces that morph around the body? How can we nurture a meaningful relationship with our dwelling spaces? How can we encourage dynamic and flexible living in urban environments? How can we provide accessible and affordable living spaces? How can we utilise architecture to achieve a complete synergy with the natural environment?

How can we maximise our resourcefulness and use of regenerative, circular systems while minimising our negative impact on the environment? How can we reimagine the physical as well as psychological role of built environments to combat the environmental crisis?

Can transient architectures contribute to preserving the longevity of planet Earth?

References

Architecture Without Architecture 2022. *ARCHIGRAM THE CUSHICLE AND SUITALOON* accessed 02 July 2022, <http://architecturewithoutarchitecture.blogspot.com/p/cushicle-and-suitaloon-were-conceptual.html>

Banham, Reyner 1957. 'Manifesto' *Journal of the Royal Institute of British Architecture*, vol. LXIV, no 4, p 129-139

Beesley, Philip et al. 2010. Hylozoic Ground : liminal responsive architecture. Riverside Architectural Press

Benyus, Jenine M., 2002. Biomimicry: Innovation inspired by nature. Harper Perennial.

BEWI 2021. *BioFoam* accessed 02 July 2022, <https://bewi.com/products/bio-foam/ >

Blast Studio 2022. *Our innovation* accessed 18 July 2022, <https://www.blast-studio.com/our-innovation>

Bloom 2016. *Algae Foam* accessed 21 July 2022, <https://www.bloommaterials.com/the-bloom-story/ >

Brown, David, et al. 2004. The Home House Project: The Future of Affordable Housing, Cambridge; The MIT Press

Cress, Kevan and Boll, Timothy 2023. Living Architecture Systems Description. Riverside Architectural Press

Ecocapsule 2022. *About* accessed 02 July 2022, <https://www.ecocapsule.sk/#about>

ECOS 2020. *From Barrier to Enabler: Towards a greeener EU construction products policy* accessed 18 June 2022, <http://rb.gy/posko>

Emerging Objects 2013. *Saltygloo* accessed 23 July 2022, <http://rb.gy/zpe09>

Franklin, Kate and Till, Caroline 2018. Radical Matter - Rethinking materials for a sustainable future. Thames&Hudson, Inc. New York

Fuller, R. Buckminster 1967. Operating Manual For Spaceship Earth, Southern Illinois University Press. p.165

Gijsbers, Roel 2006. Towards adaptability structures to extend the functional lifespan of buildings related to flexibility in future use of space. Eidenhoven University

Goodbun, Jon 2011. *The architecture of the extended mind: towards a critical urban ecology*. Ph.D. p192, University of Westminster https://westminsterresearch.westminster.ac.uk/download/4e399098f597b00fa49ae7df769e04a69906915930fcfb627bd7ab52ae607cd1/24969689/Jon_GOODBUN.pdf

Hesselgren, Sven 1977. Man's perception of man-made environment: An architectural theory. John Wiley & Sons Inc, New York

Ichioka, Sarah and Pawlyn, Michael 2022. Flourish, Design Paradigms for Our Planetary Emergency. Triarchy Press. p. 78

Kabasci, Stephan 2013. Bio-Based Plastics: Materials and Applications. John Wiley & Sons, Ltd.

Kapsali, Veronika 2021. Biomimetics for Designers: Applying Nature's Processes & Materials in the Real World. Thames and Hudson Ltd.

Keedwell, Paul 2017. Headspace: The Psychology of City Living. Aurum Press Ltd.

Keep, Jonathan 2020. *A Guide to Clay 3D Printing* accessed 18 June 2022, <http://keep-art.co.uk/Journal/JK_Guide_to_Clay_3D_Printing.pdf>

Klarenbeek & Dros - Designers of the Unusual 2011. *KROWN.bio* accessed 03 July 2022, <http://www.krown-design.com/>

Le Corbusier 2009. Towards a New Architecture. BN Publishing

Leupen, Bernard 2005. 'A New Way of Looking at Flexibility', *Open House International*, Vol. 30 No. 1, 2005: 55-61. https://doi.org/10.1108/OHI-01-2005-B0008

LTG Lofts 2022. *About* accessed 02 June 2022, <https://loftstogo.com/about/>

Kretzer, Manuel 2014. ALIVE: Advancements in Adaptive Architecture. German National LIbrary. p. 72 - 77

Materiability Research Group 2020. *Materiability* accessed 02 July 2022, <https://materiability.com>

Materiability Research Group 2020. *3D Printing Bioplastics* accessed 18 June 2022, <https://materiability.com/portfolio/3d-printing-bioplastics/>

Materiom 2022. *Materiom,* accessed 02 June 2022, <https://materiom.org>

Menges, Achim, Leach, Neil, and F. Yuan, Philip 2018. Digital Fabrication, Tongji University Press

Margulis, Lynn 2004. 'Serial endosymbiotic theory (SET) and composite individuality'. *Microbiology Today*, p.172

Mario Cucinella Architects 2021. *The first eco-sustainable housing model 3D printed from raw earth* accessed 21 July 2022, <http://rb.gy/oo8nh >

Marsh, Rob 2017. Building lifespan: effect on the environmental impact of building components in a Danish perspective, *Architectural Engineering and Design Management*, 13:2, p. 80-100, DOI: 10.1080/17452007.2016.1205471

Mogas-Soldevila, Laia, Duro-Royo, Jorge, Oxman, Neri 2015. 'FORM FOLLOWS FLOW: A Material-driven Computational Workflow For Digital Fabrication of Large-Scale Hierarchically Structured Objects' *Acadia – Computational Ecologies: Design in the Anthropocene 2015 Conference, Ohio.* <http://rb.gy/9dtv9>

Pasquero, Claudia and Poletto, Marco 2020. 'Air-purifying playground designed in Warsaw' *Icon* (2021) accessed 6 September 2021 <https://www.iconeye.com/design/air-purifying-playground-airbubble-warsaw-ecologicstudio>

Pawlyn, Michael 2011. Biomimicry in Architecture. Routledge

Peters, Sascha and Drewes, Diana 2019. Materials in Progress: Innovations for designers and architects. Birkhauser Verlag GmbH

Raby, Fiona, Dunne Anthony 2013. Speculative Everything: Design, Function and Social Dreaming. MIT Press

Rizwan, Muhammad et al. 2018. Exploring the potential of microalgae for new biotechnology applications and beyond: A review. *Renewable and Sustainable Energy Reviews 92* 2018: p.394-404, <https://www.researchgate.net/publication/325193566_Exploring_the_potential_of_microalgae_for_new_biotechnology_applications_and_beyond_A_review>

Sabin, Jenny et al. 2019. POLYBRICK 2.0: Bio-Integrative Load Bearing Structures. *ACADIA 2019 (Ubiquity and Autonomy).* 2019: 222-233.

Saraceno, Tomas 2022. *Cloud Cities* accessed 02 July 2022, <https://studiotomassaraceno.org/>

Schunemann, Esteban 2015. '*Paste deposition modelling, deconstructing the additive manufacturing process: Development of novel multi-material tools and techniques for craft practitioners*' PhD Thesis, Brunel University, London.

Seto K.C., S. Dhakal, A. Bigio, H. Blanco, G.C. Delgado, D. Dewar, L. Huang, A. Inaba, A. Kansal, S. Lwasa, J.E. McMahon,D.B. Müller, J. Murakami, H. Nagendra, and A. Ramaswami 2014. Human Settlements, Infrastructure and Spatial Planning.In: Climate Change 2014: *Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press

Shi, Yusheng, et al. 2021 Materials for Additive Manufacturing. Elsevier Science, Amsterdam

Solanki, Seetal 2018. Why Materials Matter. Prestel, Verlag, Munich

Spatial Agency 2011. *1960s Utopian Groups,* accessed 02 June 2022, <https://www.spatialagency.net/database/why/political/1960s.utopian.groups>

Termokomfort Nederland B.V. 2014. *BiofoamPearls* accessed 29 May 2022, <https://www.termokomfort.nl/isolatieparels/biofoampearls >

TERREFORM ONE 2016. *Urban Farm Pod with Agronomy* accessed 02 July 2022, <https://www.terreform.org/plug-in-ecology>

The Funabulist 2011. *# GREAT SPECULATIONS /// LIVING POD BY DAVID GREENE* accessed 02 July 2022, <https://thefunambulist.net/editorials/great-speculations-living-pod-by-david-greene>

Vasquez, Lazaro et al. 2022. *Exploring Biofoam as a Material for Tangible Interaction.* DIS '22, June p. 13–17, 2022, Virtual Event, Australia https://dl.acm.org/doi/pdf/10.1145/3532106.3533494

WASP & Mario Cucinella Architects 2021. *TECLA* accessed 03 July 2022, <https://www.3dwasp.com/en/3d-printed-house-tecla/>

Xu, Xiaoming, Sharma, Prateek, Shu, Shijie et al. 2021. Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. *Nat Food 2*, 2021: p. 724–732. https://doi.org/10.1038/s43016-021-00358-x

Yuan, Philip F., et al. 2018. Digital Fabrication, Tongji University Press, Shanghai

3D Printing Media Network 2021. *Liquid Deposition Modeling (LDM)* accessed 21 June 2022, <http://rb.gy/bdg2q>

Image Credits

Page 01 - 09	Paulina Schröder, HS Anhalt, 2022
Page 11	Claudia Palcova, London, 2022
Page 13 - 16	Paulina Schröder, HS Anhalt, 2022
Page 17 - 18	Claudia Palcova, HS Anhalt, 2022
Page 19 - 20	Paulina Schröder, HS Anhalt, 2022
Page 21 - 22	Claudia Palcova, HS Anhalt, 2022
Page 23 - 26	Paulina Schröder, HS Anhalt, 2022
Page 27 - 31	Claudia Palcova, HS Anhalt, 2022
Page 33 - 34	Chris Busch and Claudia Palcova, HS Anhalt, 2022
Page 35 - 42	Claudia Palcova, HS Anhalt, 2022
Page 43 - 44	Johann Spindler, London, 2022
Page 45 - 49	Claudia Palcova, HS Anhalt, 2022
Page 50	Kachi Chan, London and Claudia Palcova, HS Anhalt, 2022
Page 53 - 56	Paulina Schröder, HS Anhalt, 2022
Page 70 - 71	Claudia Palcova, HS Anhalt, 2022

Video Credits

Page 31	Claudia Palcova, HS Anhalt, 2022 https://www.claudiapalcova.com/printing-biofoams-video

Credits

Manuel Kretzer	Lead research supervisor | Folio editor
Virginia Binsch	Lab supervisor | Model
Chris Busch	Delta Wasp extruder adaptation advisor
Arthur Wilson	Delta Wasp direct drive adaptation advisor
Karsten Schuhl	Delta Wasp direct drive adaptation advisor
Benjamin Kemper	Additive manufacturing systems advisor
Ka Chi Chan	Concept Visualisation
Paulina Schroeder	Photography
Johann Spindler	Photography
Philip Beesley	Folio editor
Bianca Weeko Martin	Folio editor

About Collaboration

Claudia Palcova is a London-based designer and material researcher who works across experimental design and temporary spatial interventions. Her process-led work focuses on the application of novel regenerative materialities in tactile interactions to reimagine the way we perceive, understand and connect with the world around us. Learning from natural forms and systems, Claudia combines traditional craft with modern technologies in complex, multilayered designs using minimal means for maximum impact.

During her studies at the Royal College of Art, Claudia became increasingly interested in the impact materials, technologies and processes have on the environment. Focusing on non-invasive, temporary spatial interventions, she grew a more critical outlook on standardised design practices and started to look for alternative approaches that encourage regenerative material sources, circular design solutions and carbon-negative processes, in the context of built environments. As a result, she has formed extensive collaborations with specialists across biology, materials science, digital fabrication, architecture and textile design.

Materiability was first conceived in 2010 during Manuel Kretzer's doctoral research at the Chair for CAAD, ETH Zürich to bridge the gap between design, architecture and science. With projects spanning across materials science, interaction design, textile design, product design, engineering, and robotics, Materiability has quickly grown into an international community producing content across research and education. In 2020 Prof. Kretzer established the Materiability Research Group and associated Materiability Labs together with Virginia Binsch at the University Campus Dessau. The group focuses on exploring novel material fabrication in unison with digital design and fabrication processes.

A particular emphasis is on adaptive or smart technologies as well as biological materials and their impact on our future environment.

With a shared interest in regenerative materialities, innovative design solutions and transdisciplinary design practices, Claudia Palcova joined Materiability Research Group as a researcher in residency in March 2022. Building on Materiability's previous work with 3D-printed biomaterials, Claudia's research intends to explore the potential use of additive manufacturing in the construction of temporary biofoam environments. Curious about the future relationships between the biotic and abiotic ecosystem components and the potential role of new materialities, processes and technologies in combating the current environmental crisis, *Printing with Biofoams: Transient futures exploration* permeates across material research, development and speculative design.

Printing with Biofoams
Transient Futures Exploration

Claudia Palcova
edited by Manuel Kretzer

This folio is a brief representation of a biomaterial research project exploring the potential implementation of additive manufacturing in the production of temporary biofoam structures with varying zonal properties. Learning from natural systems, material sciences and digital fabrication technologies, the intention is to develop a range of printable biopolymers utilising an adaptable manufacturing system. A non-invasive, non-toxic system that responds to the unique physical and psychological requirements of individual projects in the context of temporary architectures and interior spatial interventions.

With a shared interest in innovative materials, regenerative design solutions and transdisciplinary design practices, Claudia Palcova joined the Materiability Research Group as a researcher in residence in March 2022. Building on Materiability's previous work with 3D printed biomaterials, Claudia's research explores the use of additive manufacturing in the construction of temporary biofoam environments. Curious about the future relationships between biotic and abiotic ecosystem components and the potential role of new materialities, processes and technologies in combating the environmental crisis, *Printing with Biofoams, Transient futures exploration* permeates across material research, development and speculative design.

ISBN 978-1-988366-41-8

9 781988 366418 >

Riverside Architectural Press