

SIGraDi 2024

Biodigital Intelligent Systems

XXVIII International Conference of the Ibero-American
Society of Digital Graphics Proceedings

13-15 November 2024
iBAG-UIC Barcelona (Spain)

CumInCAD



INSTITUTE FOR BIODIGITAL
ARCHITECTURE & GENETICS



Universitat Internacional
de Catalunya

SIGraDi



XXVIII International Conference of the
Ibero-American Society of Digital Graphics

13-15 November 2024
iBAG-UIC Barcelona (Spain)

© by the editors
© XXVIII Congress of the Ibero-American Society of Digital Graphics (SIGraDi)
www.sigradi.org/sigradi2024
© iBAG-UIC Barcelona, 2024.
(Institute for Biodigital Architecture & Genetics)
Universitat Internacional de Catalunya (UIC)
Immaculada, 22, 08017-Barcelona, Spain
Tel. +34-932 541 800
www.geneticarchitectures.weebly.com / www.uic.es

© in all texts, projects and images, are owned by their authors

Cover: AI aided image by © Alberto T. Estévez + Yomna K. Abdallah, December 2022

This publication has its origin in the papers of the SIGraDi 2024 - Biodigital Intelligent Systems Conference, curated by Alberto T. Estévez (Chair) and David A. Torreblanca-Díaz (Co-Chair), that was held in UIC Barcelona, 2024 November 13-15.

This publication has undergone a peer review process prior to its dissemination. All rights reserved. This publication may not be reproduced, in whole or in part, or stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission in writing of the publisher. The content of this book is the responsibility of the authors and does not necessarily reflect the opinion of the publishers. This publication has undergone a peer review process prior to its dissemination.

Editorial Sociedad Iberoamericana de Gráfica Digital
Bulevar General Artigas 1031, ciudad de Montevideo, Uruguay
ISBN: 978-9915-9635-2-5

Proceedings Editors

Pablo C. Herrera, Universidad Peruana de Ciencias Aplicadas, Peru

Paula Gómez, Georgia Tech Research Institute, USA

Alberto T. Estévez, iBAG-UIC Barcelona, Universitat Internacional de Catalunya, Spain

David A. Torreblanca-Díaz, Universidad Pontificia Bolivariana, Chile-Colombia

Proceedings Automation and Indexation

Gabriel Wurzer, ProceeDings/lite/, TU Wien, Austria

Bob Martens, CumInCAD, TU Wien, Austria

These proceedings contributed to the development of ProceeDings 2.0, under the charter laid out in the executive meeting of the SIGraDi.

Organization

SIGraDi 2024 - Biodigital Intelligent Systems Conference is hosted by the iNSTITUTE FOR BiODiGITAL ARCHITECTURE & GENETICS (iBAG) at Universitat Internacional de Catalunya (UIC) in Barcelona, Spain, and supported by the SIGraDi Executive International Committee (CEI) and the SIGraDi Advisory Committee (CA).

Alberto T. Estévez, iBAG-UIC Barcelona

Chair

David A. Torreblanca-Díaz, iBAG-UIC Barcelona / Universidad Pontificia Bolivariana

Co-Chair

Yomna K. Abdallah, iBAG-UIC Barcelona

General Coordination

Affonso Orciuoli, iBAG-UIC Barcelona

Institutional Relations

Local Organizing Committee, iBAG-UIC Barcelona

Julia Almaraz, Natalia de Andrade, Pablo Baquero, Cristóbal Becker, Daniela Frogheri, Effimia Giannopoulou, Pablo Lorenzo-Eiroa, Konstantina Melachropoulou, Alexis Méndez, Justyna Morawska, Nohemi Pacheco, Sandra Sánchez, Nadin Tarek, Ariel Valenzuela, Cristian Vinicius, Angad Warang, Emad Zarifzakerianmosibat, Naomi Zaucedo

Sponsors

Platinum

Gold

Bronze



Master
Program in
Biodigital
Architecture



Printable Morphologies: Harnessing the 3D printing potential of generative distinct forms

Sema Alaçam¹, Jose Pedro Sousa², Orkan Zeynel Güzelci^{1,2}, Pedro Martins Carvalho^{2,3}

¹Istanbul Technical University, Istanbul, Türkiye, ²University of Porto, Porto, Portugal, ³University of Coimbra, Coimbra, Portugal

alacams@itu.edu.tr; jsousa@arq.up.pt; guzelci@itu.edu.tr/oguzelci@arq.up.pt; pmcarvalho@uc.pt

Abstract. 3D Construction Printing (3DCP) process is one of the most relevant trends nowadays. However, to fulfill its formal, sustainable, and economic promises, the exploration of 3DCP requires critical thinking and efficient design. This paper describes a two-week-long student workshop at Istanbul Technical University (ITU) focused on exploring and producing design forms that justify the use of 3DCP. After introducing the class and design brief, it describes the workshop experience and shares its main results. The outcomes are then analyzed in four main topics: (i) design strategy, (ii) geometry, (iii) openings, and (iv) printing strategies. To assess the teaching experience, a three-question survey was conducted to gather students' feedback. Lastly, the pedagogical experiment is discussed based on the workshop outputs and feedback, and projections are provided for the development of future education/workshops of similar scope.

Keywords: Digital fabrication and Industry 4.0, 3D construction printing, Generative systems, Form exploration, Pedagogical experiment

1 Introduction

3D printing is not a new technology and has been evolving for decades. Initially, it was used in architecture for the production of small-scale physical models aimed to support experimentation and design decisions. Such models have been useful in producing better-informed alternatives by allowing various physical experiments throughout the architectural design process.

More recently, with the development of larger 3D printing machines, the focus has shifted from small-scale prototypes to full-scale production of

architectural products, components, and buildings. However, 3D Construction Printing (3DCP), on the other hand, brings with it novel challenges, such as:

- the inadequacy of existing structural strength regulations to address this new mode of construction;
- the development of sustainable and cost-effective materials to support additive processes;
- the design of architectural forms that justify the selection and use of this construction technology over conventional methods.

Therefore, the emerging challenges outlined above indicate the necessity for new research directions in architecture, which should also encompass educational contexts. However, directly introducing 3DCP into architectural education can be challenging. One potential risk is that students may become constrained by designing for methods that can be easily achieved using traditional construction techniques. On the other hand, the inherent ability of 3D printing systems to materialize almost any kind of geometry can also result in a superficial and acritical relation between design and materialization technology.

In this context, this paper presents a teaching experiment (workshop) focused on exploring purposeful connections between 3D printing technologies and form creation through generative approaches. By addressing generative and parametric design issues in conjunction with current production technologies, the workshop aimed to develop a critical perspective among students regarding the role of design in uncovering the potential of 3DCP processes in architecture.

1.1 Background

The field of 3D Construction Printing (3DCP) can be traced back to 1998, when Behrokh Khoshnevis and Rosanne Dutton introduced an innovative rapid prototyping technique called Contour Crafting. This additive technique was notable for its ability to produce large, smooth-surfaced, complex shapes across various materials using a layer-by-layer approach (Khoshnevis and Dutton, 1998). Twenty years ago, Khoshnevis (2004) explored potential applications of Contour Crafting, intending to integrate it with other robotic and information technologies to create an automated construction system. Khoshnevis (2004) also suggested that this system could be used to construct entire buildings, using materials such as concrete, smart concrete, fiber-reinforced plastics, and various additives.

In 2008, Enrico Dini developed D-Shape, a pioneering 3D printing technology that enabled the free-form construction of large-scale monolithic structures without the need for formwork or molds. The Radiolaria Pavilion, designed by Andrea Morgante of Shiro Studio in 2011, explored the capabilities of D-Shape technology, using a powder-based material composed of an inorganic binder and calcium magnesium carbonate (Morgante, 2017) (Figure 1a). A paper by Buswell et al. (2007) introduced Freeform Construction, a concept utilizing digital fabrication for the creation of complex, custom, large-

scale structures that differ from traditional construction methods. This approach, similar to 3D concrete printing, allows for the design of complex architectural forms that would be challenging or impossible to achieve with conventional techniques.

In 2013, Winsun, a company based in China, began 3D construction printing by producing a series of houses. The construction process involved prefabricating building components, such as walls, in a factory and then transporting and assembling them on-site. Although innovative in terms of construction methods, the forms and appearances resembled typical houses (Winsun, 2016) (Figure 1b). In 2021, the first 3D-printed house in the Netherlands was constructed in Eindhoven through a collaboration involving the Eindhoven University of Technology (TU/e), the Municipality of Eindhoven, and industry partners Van Wijnen, Saint-Gobain Weber Beamix, Vesteda, and Witteveen + Bos. Named 'Project Milestone,' this initiative demonstrated advancements in 3D construction printing and its contribution to freedom in design form. In Project Milestone, the house, which appears monolithic, had its parts prefabricated off-site and then assembled on-site (Wolfs et al., 2023) (Figure 1c).

Also in 2021, the TECLA project, a collaboration between WASP and Mario Cucinella Architects, utilized 3D printing technology and sustainable local materials, such as clay. WASP's Crane, a modular 3D printer, enabled efficient execution by synchronizing multiple printing arms on the construction site. This project highlights the potential of 3D construction printing to develop new, sustainable construction methods using local materials (Moretti, 2023) (Figure 1d).

The development and commercialization of 3DCP technologies for concrete construction have accelerated their use in the residential market. A notable collaboration between ICON, an innovative construction and technology company, Lennar, a residential builder, and BIG, a renowned architectural firm, further demonstrated this progress (Designboom, 2021) (Figure 1e). A project developed by the European Space Agency (ESA) and Foster + Partners focused on creating a lunar habitat using robot-operated 3DCP technology and lunar soil and regolith as local materials. Although largely conceptual, this project proposed a shell structure that exemplifies the application of 3DCP in an extraterrestrial setting (Foster + Partners, 2012) (Figure 1f).

The number of research and applications on 3DCP continues to increase and remains updated. In a recent review article, Hassan et al. (2024) discussed technological advancements, material innovations, sustainability efforts, and geometric explorations as crucial factors for research, development, and practical applications in the field of 3DCP.

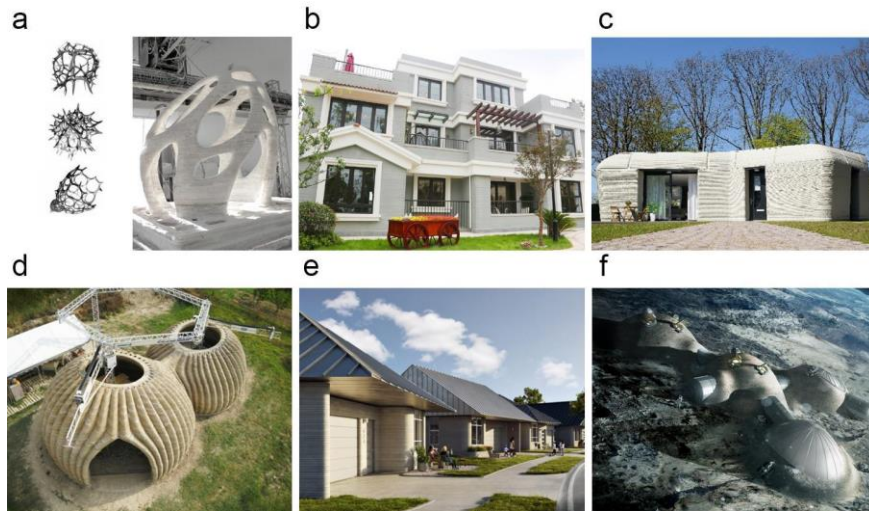


Figure 1. Various examples of 3DCP. Source: (a) Morgante, 2017; (b) Winsun, 2016; (c) Wolfs et al., 2023; (d) Moretti, 2023; (e) Designboom, 2021; (f) Foster + Partners, 2012.

2 Method

Generative Systems in Architectural Design (GSAD) is a course in the Architectural Design Computing Graduate Program at Istanbul Technical University (ITU). As one of the compulsory courses in the program, GSAD focuses on examining architectural design within the context of contemporary design paradigms and aims to provide knowledge on the role and applications of generative processes in architectural design.

The course is 14 weeks long, with weekly 3-hour in-person classes. Through a combination of theoretical lectures and practical applications, students are expected to enhance their skills in computational design while engaging with generative systems.

In the spring semester of the 2023/2024 academic year, the GSAD course had 29 students. To inform students about how generative design topics are addressed with current production technologies and to provide them with practical design experience, an intensive 2-week workshop was organized at the beginning of the semester. This workshop, limited to enrolled students, took place during the weeks of 26 February and 4 March 2024. During the 2 workshop weeks, the course hours were extended to 5 hours per day. This schedule included 2 hours of lectures before the regular course hours, followed by 3 hours of experimental sessions under the supervision of tutors.

The primary aim of this workshop was to explore forms that could benefit from using 3DCP processes and thus justify their use. As a subsequent goal,

the workshop aimed to introduce students to the use of generative design processes in architecture. Prior to giving the workshop brief, students were informed about 3DCP (by second author) through a presentation on the state of the art. Subsequently, two interactive tutorials were conducted: one on the basics of Rhino/Grasshopper and the generation of shell geometries (by first and third author), and another on obtaining two-dimensional representations of the produced geometries (by fourth author). Due to the workshop being limited to two class days, no additional training on the use of 3D printers was provided.

According to the workshop brief, the students were expected to explore shell geometries that (i) could be produced using a parametric and/or generative design approach in the Rhino/Grasshopper environment, (ii) had a spatial quality, (iii) did not include conventional building components such as a roof, window, or door, and (iv) could be prototyped with a 3D printer without any support. In addition to the assignment brief, students were asked to keep the following two questions in mind throughout the entire process:

- Does the produced geometry justify the use of 3DCP?
- Does the produced geometry maximize the use of 3D printing?

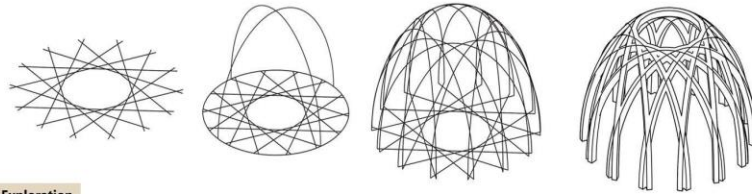
After receiving the design brief, the students began conducting their individual form explorations. Subsequently, they started prototyping the form alternatives they had produced using a 3D printer. Throughout this process, the students learned from the 3D prints and continued refining their shell designs and prototyping during the second week of the workshop. During these phases, tutors provided support both in person (first and third authors) and online (second and fourth author) by assisting with technical issues. The tutors also clarified any aspects of the brief that were not understood, rather than criticizing the students' conceptualizations.

3 Results

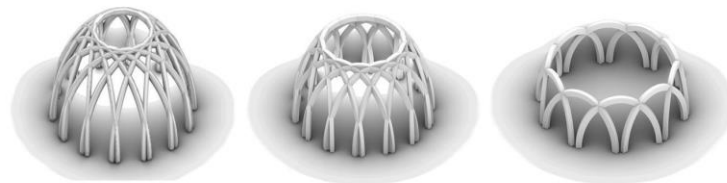
At the end of the workshop, the students submitted panels that included sketches from the development phase, 2D and 3D drawings, and Grasshopper definitions, along with physical models (Figure 2). Figure 3 showcases the collection of final results from the students' submissions. From the simple exercise brief and the diverse set of works, several paths can be identified that categorize the students' outcomes in response to the questions posed, forming an interesting picture of 3Dprinted morphologies within the scope of this exercise.

Workshop* Generative Systems in Arch. Design
MBL 512 Spring 2023-2024

Printable Morphologies



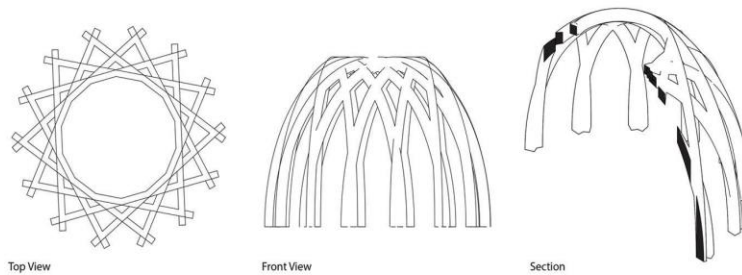
Exploration



Variation



Definition



Representation

Figure 2. Example of a submitted poster by students. Source: Authors, 2024.

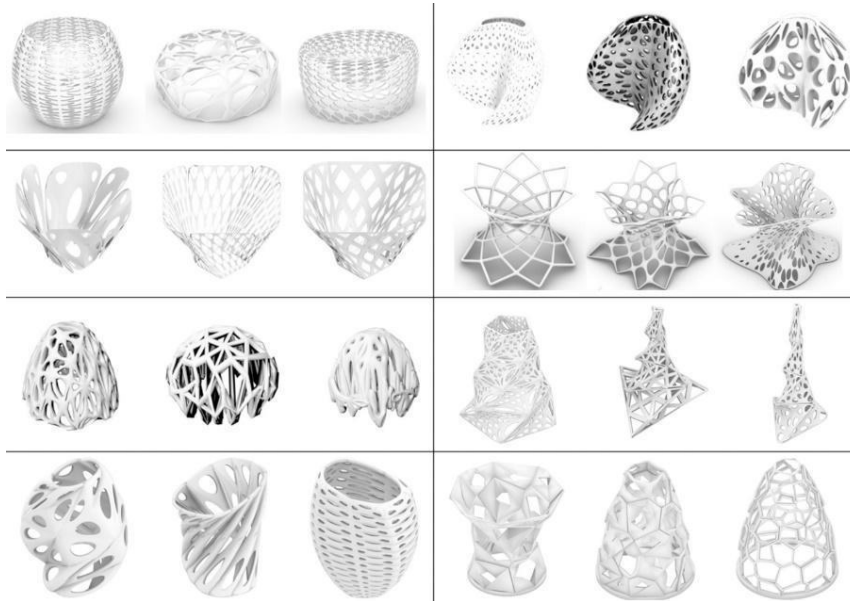


Figure 3. A selection from students' form explorations. Source: Authors, 2024.

In that regard, a set of recurring keywords in four main categories—(i) design strategy, (ii) geometry, (iii) openings, and (iv) printing strategy—were identified. Regarding the developed design strategies, most of the students' works were created using common parametric design and form-finding processes, which involved defining an underlying shape or module that was subsequently repeated, transformed, or subdivided to achieve the final shell designs.

The main design strategies used were lofting (Figure 4a) and physical simulations (Figure 4b) in most cases, with some students opting to use modules and polar arrays (Figure 4c) to define more discontinuous solutions. Another operation employed to achieve varied iterations was twisting (Figure 4d), which was used to create interesting curved surfaces. Most works also incorporated some form of surface subdivision, either through random population (Figure 4e) or paneling (Figure 4f).

Regarding overall geometry, the resulting works could be categorized into one of four types: (i) continuous double-curved surfaces (Figure 5a); (ii) discontinuous curved surfaces; (iii) discontinuous planar surfaces; and (iv) ribbed structures (Figure 5b). Most students explored openings at various scales in the definition of their printable morphologies, either appearing in periodic or aperiodic patterns, with only one student working with a continuous closed surface.

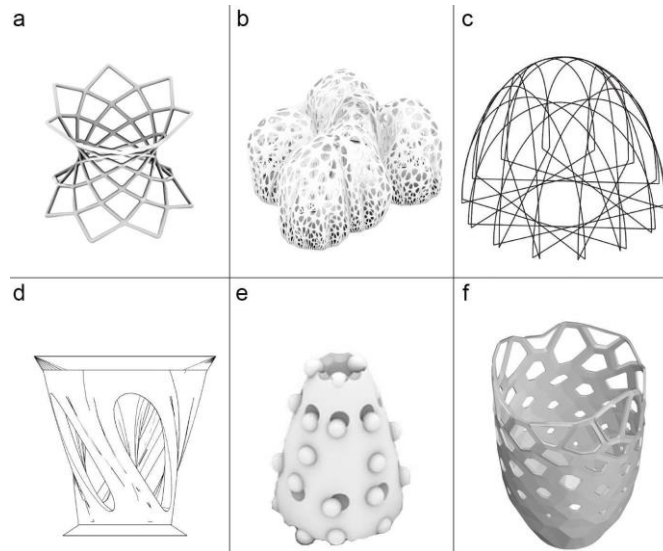


Figure 4. Various design strategies adopted by students. Source: Authors, 2024.

Regarding the 3D printing task, different strategies emerged, reflecting the variety of designs that each student developed and their suitability for 3D printing. During this stage, students alternated between initial printing tests and design reviews, correcting issues that hindered the printing process. Two main considerations were taken into account: (i) printing position and (ii) supports. In terms of printing position, some students optimized printing by changing the model's orientation within the printing volume. However, this was not ideal for this exercise, given the simulation of the 3DCP process, so these students redeveloped their shapes or repeated printing while considering only upright printing. As for supports, students either used automated supports or designed removable supports (Figure 6a; Figure 6b). Some students revised their geometries to be printable without supports, while others redesigned their shapes to incorporate supports into specific areas where needed (Figure 6c; Figure 6d).

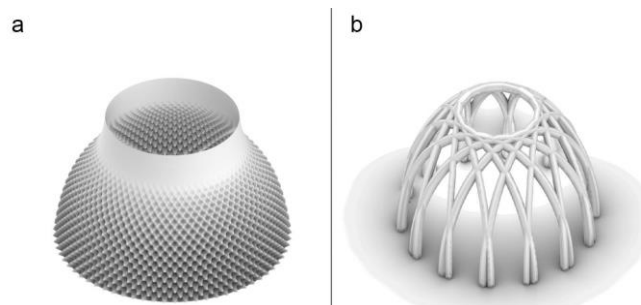


Figure 5. Various overall geometry types. Source: Authors, 2024.

3.1 Assessing the Experience and its Results

At the end of the semester, a survey consisting of three open-ended questions was prepared to gather feedback from students about the workshop process and their experiences. The questions were as follows:

1. What challenges did you encounter during the form generation and prototyping process?
2. Was nature a source of inspiration for you during the form generation and prototyping process?
3. During the form generation and prototyping process, did you primarily focus on form-finding, or was functionality (such as spatial relationships, openings like windows/doors, etc.) also a guiding factor?

Additionally, students who indicated that they were inspired by nature during the workshop were asked to share images of the natural forms that inspired them or that their creations resembled.

In response to Question 1, students encountered several challenges during the form exploration and prototyping process such as:

- A notable challenge was the students' limited expertise in using software to generate G-code for 3D printing.
- Many students struggled with 3D printing forms without support, leading to issues with thickness adjustment and the solid-void ratio, which caused fragility or structural instability in their models.
- Extended production times with 3D printers and the impracticality of continuous monitoring posed significant challenges.
- Time constraints limited the students' ability to engage in trial and error.
- The insufficient level of detail in the workshop brief resulted in ambiguity regarding design goals and requirements.
- The simplicity of the introduced algorithms limited the variety of outputs, requiring students to add extra components to enhance diversity.

In response to Question 2, students' views on whether nature served as an inspiration during the form generation and prototyping process varied:

- Students working with less complex forms did not derive inspiration from nature.
- Students focusing on structures with porosity found significant inspiration in natural formations.
- Students prioritizing functionality did not initially use nature as an inspiration. However, during the form exploration process, they noticed similarities between their designs and natural forms. Recognizing this, they later incorporated natural references to fine-tune aspects like the solid-to-void ratios.

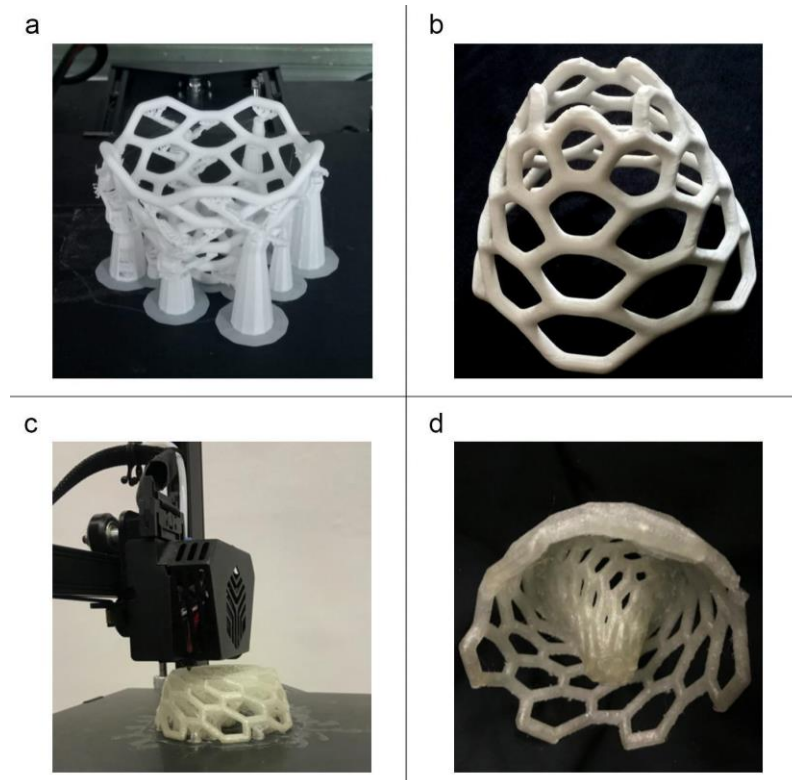


Figure 6. Different 3D printing strategies. Source: Authors, 2024.

In response to Question 3, the students' focus during the form generation and prototyping process varied, revealing different design priorities:

- A significant emphasis on form-finding was observed during the design process.
- Environmental factors played a crucial role for some students, indicating the integration of performance considerations into their designs.
- For some, the constructability of the generated form was considered a functional aspect.
- A notable approach involved maintaining a dual focus on form-finding while ensuring structural integrity and human scale.

Students who found inspiration in nature shared images of natural forms, which included bone tissue, weeping willow trees, fossilized plant cells, bird nests, sponge morel fungi, and coral reefs.

4 Discussion

With a pedagogy focused on exploring the relationships between specific digital fabrication technologies and their potential design morphologies, the two-week workshop provided valuable insights into possible design logics for 3DCP, while also uncovering some natural design tendencies revealed by the students. Some of the key findings from this experience include:

- Printable morphologies primarily consisted of various curved domed surfaces. In addition to surface geometry, the concept of porosity was a major design topic explored by the students. Observing these two trends suggests that students have a natural interest in exploring bio-inspired forms.
- The variation of designs often proved difficult to control, indicating a need for extended training to better manage formal variety through generative algorithms.
- The limited duration of the workshop restricted the exploration of multiple form alternatives due to extended printing times. However, when this did occur, it showcased interesting back-and-forth explorations, focused on the printability of certain formal concepts. This constraint emphasized the need for more efficient 3D printing planning and time management for iterations.
- An interesting design consideration bridging design and 3D printing was the students' strategies regarding printing supports. However, this aspect may not directly relate to 3DCP processes and should be further explored in future investigations.

The study's findings suggest that incorporating natural references can significantly enhance form exploration and optimization. Students utilizing generative and/or parametric design approaches inevitably began designing and producing nature-inspired forms, sometimes recognizing this tendency only in hindsight. This outcome may be attributed not only to the inherent characteristics of these design methodologies but also to an understanding of the specific conditions of 3DCP processes.

In the pedagogical context, the results of the workshop highlight the need for further development and a potential revisiting of the syllabus and schedule to better accommodate the challenges of 3DCP. For example, constraining design exploration to 3D digital modeling alone might have been sufficient to achieve the workshop's goals within the two-week timeframe. The inclusion of generative design processes introduced a higher level of complexity that was difficult to manage alongside the goal of examining 3DCP's potential.

Finally, at this educational level, it is crucial to understand the logic of 3DCP technology, including its constructability, effectiveness, and time parameters. This comprehensive understanding will better prepare students for future innovations and applications.

Acknowledgements. The authors would like to thank all the students enrolled in the Generative Systems in Architectural Design course during the spring semester of 2023/24, which took place at ITU. This work was developed by the Digital Fabrication Laboratory (DFL) within the CEAU at FAUP, in collaboration with faculty members from ITU. This paper was partially supported by national funds through FCT – Fundação para a Ciência e a Tecnologia, I.P., under project UIDB/00145/2020. It was also supported by the Scientific Research Projects Coordination Unit (BAP) of ITU under project FHD-2024-46341.

References

- Buswell, R. A., Soar, R. C., Gibb, A. G., & Thorpe, A. (2007). Freeform construction: mega-scale rapid manufacturing for construction. *Automation in construction*, 16(2), 224-231. <https://doi.org/10.1016/j.autcon.2006.05.002>
- Designboom. (2021). BIG and ICON to create world's "largest neighbourhood" of 3D-printed homes. <https://www.dezeen.com/2021/11/01/icon-and-big-worlds-largest-neighbourhood-3d-printed-homes/>
- Foster + Partners (2012). Lunar Habitation. <https://www.fosterandpartners.com/projects/lunar-habitation>
- Hassan, H., Rodriguez-Ubinas, E., Al Tamimi, A., Trepce, E., Mansouri, A., & Almehairbi, K. (2024). Towards innovative and sustainable buildings: A comprehensive review of 3D printing in construction. *Automation in Construction*, 163, 105417. <https://doi.org/10.1016/j.autcon.2024.105417>
- Khoshnevis, B. (2004). Automated construction by contour crafting—related robotics and information technologies. *Automation in construction*, 13(1), 5-19. <https://doi.org/10.1016/j.autcon.2003.08.012>
- Khoshnevis, B., & Dutton, R. (1998). Innovative rapid prototyping process makes large sized, smooth surfaced complex shapes in a wide variety of materials. *Materials Technology*, 13(2), 53-56. <https://doi.org/10.1080/10667857.1998.11752766>
- Moretti, M. (2023). WASP in the Edge of 3D Printing. In *3D Printing for Construction with Alternative Materials* (pp. 57-65). Springer International Publishing. https://doi.org/10.1007/978-3-031-09319-7_3
- Morgante, A. (2017). Radiolaria pavilion. In *Fabricate 2011: Making Digital Architecture* (231-234). UCL Press.
- Winsun. (2016). Autoridades. <https://www.futureofconstruction.org/video/winsun-demonstrating-the-viability-of-3d-printing-at-scale-in-construction/>
- Wolfs, R., Bos, D., & Salet, T. (2023). Lessons learned of project Milestone: The first 3D printed concrete house in the Netherlands. *Materials Today: Proceedings*. (in press) <https://doi.org/10.1016/j.matpr.2023.06.183>

Photos: AI aided images by © Alberto T. Estévez + Yomna K. Abdallah

Editorial Sociedad Iberoamericana de Gráfica Digital
Bulevar General Artigas 1031, ciudad de Montevideo, Uruguay
ISBN: 978-9915-9635-2-5