The one chair, that is made for you

Antonio Scaffidi
Institut for Bygningskunst og Design,
Det Kongelige Akademi - Arkitektur, Design, Konservering, Copenhagen, Denmark
e-mail: asca@kglakademi.dk

Jakob Sieder-Semlitsch
Aarhus School of Architecture, Aarhus, Denmark
e-mail: jss@aarch.dk

Abstract

This research presents a method to design and fabricate a task chair tailored to individual and specific data of the end-user. The aim is to respond to the question of a functional bespoke mass product and to reduce parts and production complexity to a mono-material geometry with arguments for circularity. This is done with a robotic setup with the application of conformal 3d printing. The specific application in the case of a task chair is chosen as a mid-scale object with the possibility of clear performance evaluation. The project explores the proposed systems from data collection to final product production, and investigates its performance towards linking user data, design process and robotic fabrication methods. The findings are a result of a design-based research methodology, which allowed for a dynamic and adaptive investigation into the subject. For this, the paper will articulate the fabrication setup, illustrate experimental testing and evaluate findings, as well as hypothesizing on design cases as demonstrator.

1. Introduction

Polymer based consumer goods are commonly produced through thermoplastic injection molding techniques, based on finite tooling design strategies, most often injection molding. This highly optimized industry standard outperforms any other fabrication method in cost per item, production cycle times and quality consistency [1]. However, conventionally injection molding relies on prefabricated steel multi-part tooling and is incontrovertibly biased to the tool itself, thus incapable of variations in e.g. shape, size and strength. While, since 2009 the field Additive Manufacturing (AM) has rapidly grown in application, utilization and accessibility, the technology is only now being implemented in large scale fabrication [2]. Since AM is not bound to fixed tooling, but instead utilizes selective deposition of material where needed, it allows for opportunities over other mass fabrication technologies, specifically in regard to material efficient and customizable production, but compromises – to date - on production speed, costs and quality.

This research investigates the possibilities for designing objects with variable systems for individual fabrication with large scale AM, specifically conformal polymer extrusion through Fused Deposition Modelling (FDM). This focusses on identifying quality and design expression regarding its geometrical and extrusion parameters. For this, the study aims at designing and producing functional consumer items within parametric variable boundaries, thereby allowing for user or context customization of polymer-based items. The study focusses in two parts at (1) establishing a robotic 3D printing system to facilitate an experimental process of design fabrication with polylactic acid (PLA) material, industrial grade pellets; and (2) to investigate design intends to evaluate and proof plausible and beneficial variations within design systems – parametric generative design. This explores a design method and strategy for adaptation of user data into an applied design context – a task chair.

2. Background

Task chairs are highly regulated functional furniture, by e.g. DIN EN16139 [3], ANSI/BIFMA X5.1-2017 [4] for work environments in regard to their dynamic seating properties, stress capability, and user adaptability. Many design solutions therefore incorporate kinetic motion mechanics to accommodate flexible sitting behavior, contributing to a healthier work environment and increased work performance [5]. However, fine adjustments are commonly only applied on initial use for a single individual. The proposed method for the fabrication of an individual chair is referencing user data for seat, backrest, height, as well as material compliance and weight distribution, aiming towards dynamic sitting behavior.

3. State of the Art

With vast advances in AM in recent years, applications at larger scales have been widely demonstrated. Within this research a subgroup has been focusing on 3d printing detached from a horizontal layer structure, as demonstrated throughout various scales for objects, e.g. by Hong [6], furniture, e.g. by Soler et al [7], or building components, e.g. by Nicholas et al. [8], Battaglia et al. [9], Branch Technologies C-Fab [10] . Moving beyond standardized printing has brought many advantages to the field, a.o. in regard to mechanical performance, visual appearance or artistic expression [11]. Specifically, the conformal 3d printing process offers, for the here described process, advances over planar layer printing [12], by application of fused material onto a previously fabricated CNC milled formwork, providing desired underlying curvature. This leads to finer surface finish [13], [14] and allows for increased mechanical behavior of the fabricated part [15], [16].

4. Method.

The project is based on an experiment driven approach, including material studies of the extruded PLA lamination, computational design pattern - generation, computational analysis and prototype experiments. The research conducted employed the methodology of research by design and weighs artistic values such as perceptions of emerging results in terms of tactility and density of material, structure, and clarity in understanding and perceiving form and function.

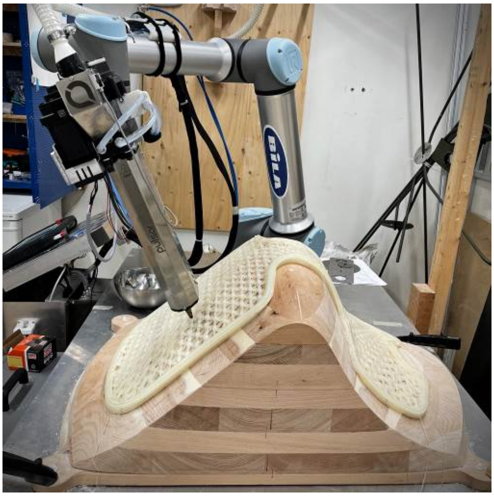

Figure 1: Robotic 3D printing setup.

Figure 2: 3D printed study from earlier chapters of the project.

A generative approach is applied towards the creation of a design as well as towards producing printable geometry, adaptive to user data. The process generates parameters for material application, density, and distribution. Further geometrical elements are therethrough directed anticipating the required behavior of the fabricated product. Varying pattern configuration are used as supporting element, ranging from compliant structures connecting seat and backrest to ridged configurations aiding mechanical performance below the seat geometry. The generated design is then fabricated by robotic conformal 3d Printing via a UR10e [17] equipped with a DYZE Pulsar [18] pellet extruder.

4.1 Print path creation

In previous study cases, we have explored performative aspects of our setup in relation to print settings on 2D print layering. (see figure 1)

We discovered a reliable relation of object dimensions, fixed extrusion rates with a nozzle size of 2mm, extrusion temperature of 225°C and an adaptable variable travel speed. Adequate layer heights ranged from 1 to 1.6mm with increased results at the coarser end of the spectrum. However, printing conformal onto three-dimensional tools required higher tolerances, attributed largely to the deviation of the physical tool from the original computational reference. More consistent visual appearances have been achieved with a 5mm nozzle and layer heights of 3-5mm. Further, an increase in extrusion temperature to 235-240°C has been successful, as this seemingly allows for the re-melting of previously distributed material. This allows for potential exceeding of given tolerances, by limiting collision impact with appearing fabrication artefacts. The coarser print resolution further allows obtaining higher volume extrusion rates, significantly lowering production times.

4.2 Design space

The investigation focused in the initial phase on the development of a robotic conformal 3D printing setup, then on a computational design system for a functional chair with adaptability for specific user data. To keep complexity minimal, user data was collected by taking measurements and weight of three different users in an analog approach.

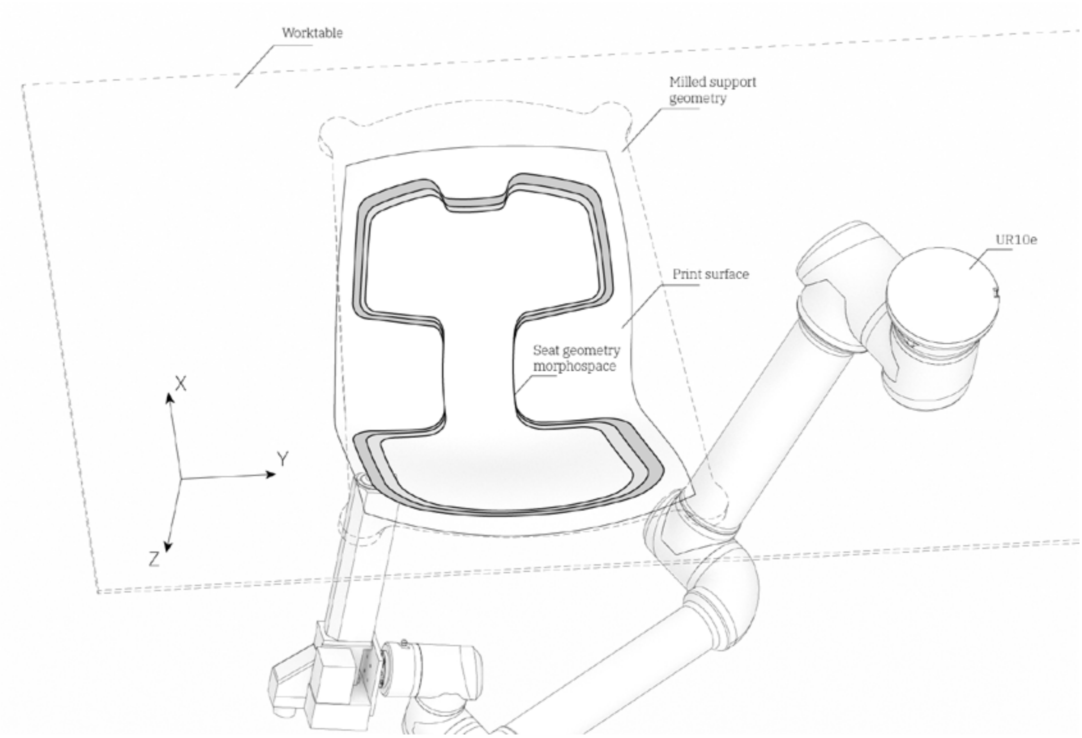

Figure 3: Seat geometry design space.

User	Height [cm]	Weight [kg]
Karen	168	54
Mads	174	110
Kresten	203	92

Table 1: User base data overview.

The significant differences in height between Kresten and Karen indicate the need of adjustment of seat height, depth and backrest. Karen´s sitting height is prompted to 440mm, Kresten will be most comfortable at 480mm sitting height. The static load of Mads requires the chair to carry almost twice the weight of Karen. In comparison Kresten and Mads have a difference of only 16,36% in weight, but the weight is distributed quite differently onto the chair, due to the difference in body proportions of both users. The proposed method, therefore suggests to accommodate user weight and proportions into the computational model, and thereby optimizing the chair for the user by bespoke fabrication.

5. Design experimentation

The reference object for the research is the KEVI chair by Jørgen Rasmussen [19], designed in 1958. The KEVI Chair is regarded as a light task chair with basic adjustability in sitting height and the pivoting backrest height. Notably, it was the first office chair with double castor wheels, which then became industry standard. To accommodate user specific adjustments, this chair is nowadays equipped with a gas-spring levitating mechanic and a mechanical fitting for backrest height adjustment [20].

Figure 4: KEVI chair by Jørgen Rasmussen [20].

The aim for this research is to address the following requirements for adaptability in the chair design: Geometrical requirements, such as sitting height, seat size including width and depth, back rest size including width and depth. Longitudinal distance between seat and backrest. For the structural requirements weight and weight distribution was prompted to call for material distribution and structural build-up of reinforcing elements such as rips and varying section dimensions.

Conducted experiments investigate providing the desired mechanical performance, optimized for the specific user data, while at the same time accommodating dynamic seating behavior, through allowing for slight motion and flexibility through compliant material and structural properties.

5.1 Material exploration

PLA pellets are utilized as a mono-material for the fabrication of all objects within this research. PLA by Nature Works Ingeo© 3D870 Natural PLA Plus are produced from corn-starch. The material is categorized as a thermoplastic biodegradable bio-polymer, with lower heat resistance compared to some other plastics like ABS (Acrylonitrile Butadiene Styrene), so it softens at relatively low temperatures, which makes it suitable for lower extrusion temperatures. PLA is generally considered safe and has low toxicity levels in this application, which favors large scale 3D printing with exposure of considerable volatile emissions by molten polymer materials. PLA is widely used in 3D printing due to its ease of use, reliability and wide availability [21].

Polylactic Acid advances for this application, due to the material´s ability to be recycled. Being a thermoplastic polymer, a simple mechanical grinding process reconverts the object in 2-3mm granules which can be reused through our 3D print setup directly [22]. At this point the research does not investigate the material´s degradation of quality by simple reusing. PLA is also adequate for advanced recyclability through hydrolyzation, which splits molecular formations back into lactic acid monomers, indicating possible advances for continued re-use over fossil-based plastics [23].

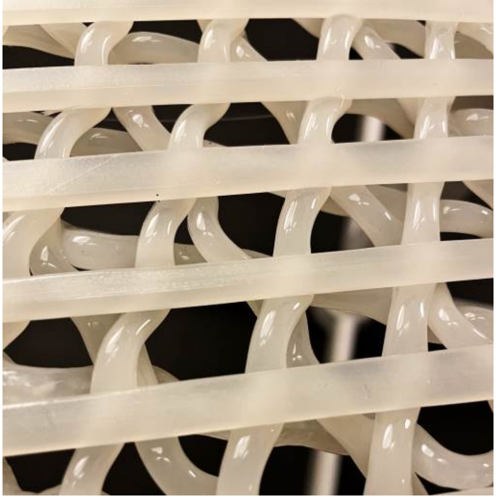

Figure 5: Patterning, contact conditions.

Figure 6: Layer lamination.

Conventional polymer injection molding results in homogenous isotropous material behavior within an object. However, the distribution of polymer by 3D printing will lead to various conditions through lamination of layers in certain directions. Generally regarded: a) overlapping contact conditions will form bonds locally at points (see figure 5), b) layering build-up contact conditions will form bonds along the print path (see figure 6) and c) negative space between print paths remain empty and do not contribute to material strength.

The evaluation of several samples has shown, the most frequent reason for fatigue failure is de-lamination of 3D print layers under stress. Followed by PLA elongation at break 7-10% caused by bending deformation of the relatively brittle polymer [24].

5.2 Computational building strategies.

The computational model for the chair was created in Rhino3d [25] and Grasshopper [26]. Two separate approaches were utilized. (1) The first step defines the geometrical surfaces of seat, backrest and the connecting backbone. User data is responsible for the chair´s proportions. Width and depth of both seat and backrest are measured prompted. Surfaces will be generated by laminating several layers in varying directions, followed by several layers of circumscribing, reinforcing contours. The emerging surface defines the size and shape of the chair but would not be strong enough to carry a human. (2) The second step generates supportive rip-structure underneath and behind the chair. Main deflection areas, caused by load stresses, are located at the backbone between seat and backrest.

6. Discussion

6.1 Material properties & degradation

PLA as a material, while exhibiting an array of favorable attributes in the projects, currently lacks application in production at larger quantities. Its brittle and less impact-resistant properties, especially compared to some other plastics, limit its suitability for larger scale production and long-term use. At the same time Current research in PLA composition suggests more favorable compositions, allowing for higher elasticity, as conducted by Pond global [27].

6.2 Printing strategy

The process explored the construction of geometry tailored to user data. Within the scale of the project, certain assumptions have been made, especially in regards to load carrying performance of the fabricated objects. Additional research is necessary to understand the materials performance under various load scenarios. To limit the complicity of the structural predictions, the fabricated chairs geometry is assumed to work as a single shell. It is to be expected, that the physical material configuration resulting from the printing process, such as layer lamination, printing direction etc., have a large influence on its performance and need to be taken into considerations.

Further a range of challenges have been observed in the fabrication process. Deviation of actual geometry of the support geometry and its ideal digital model. Small variations of that geometry, which can be attributed to the supports fabrication and scale, can cause unwanted variations in the 3d printed resulting object, ranging from cosmetic artifacts to disruptive defects causing delamination of the print from its support geometry, or collisions between the printing nozzle and previously supplied material.

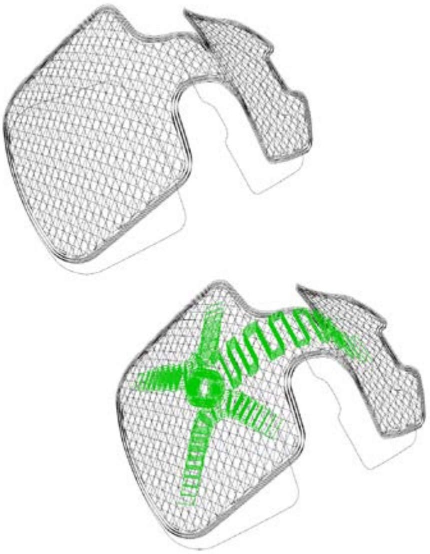

Figure 7: Geometry construction.

Large geometrical variations in the support geometry brought additional challenges for the printing process. This can be attributed to the scale of both the workpiece and of the used articulated robot's limiting reach. This results in inconsistent application of material, depending on the direction of movement of the extruder, causing material to be dragged or pushed. This requires close attention to positioning of the extruder, robotic arm over time. A current understanding of the production of code for execution does not allow to incorporate this information. This requires the introduction of a new way of treating the machine code, allowing for possibly fabrication-aware applications, through e.g. observation during the print or simulations of material distribution. This might further allow monitoring of observable material deformation, such as sagging, warping or other temperature related deformation.

6.3 User data

The user data, surveyed from the chair’s future user has been simplified for its direct application and application of the to be fabricated geometry. Past developments, observable in e.g. in sports apparel, show pathways for more automated and development of larger data sets from the user. This could allow for the inclusion of additional data, such as asymmetrical force distribution, through force sensor implementation.

7. Conclusion

Our research hypothesis asked for a method to design and fabricate a task chair, tailored to individual and specific data of the end-user investigating a feasibility for the fabrication of a bespoke mass product in a printed mono-material configuration. Our investigation discovered plausibility for a computational design model, that can respond to bespoke user data and thereby generate geometry for individual fabrication. The project also succeeded in the development of a setup for conformal robotic 3D printing. However, the scope of complexity within this application leads us to reduce many aspects significantly to isolate and understand specific challenges with the computational model, as well as the need to overcome specific challenges with our extrusion-based 3D print method. In conclusion, our findings at this stage encompass a method for addressing user-explicit body proportions to ergonomically beneficial conditions within a mono-material geometry. Further research is needed for sufficient response to a more comprehensive extend of user data, including opportunity of adaptation of the computational design model to predictive and responsive material behavior.

Figure 8: Chair demonstrator.

8. Acknowledgement

The project was financed as part of the Artistic Research project call 2022 at the Royal Danish Academy, Copenhagen, Denmark, and was conducted as part of a three-year special funding for Artistic Research by the Danish Government.

References

[1] “Injection Moulding - an overview

| ScienceDirect Topics.” Accessed: Nov. 08, 2023. [Online]. Available: https://www.sciencedirect.com/topics/engineering/injection-moulding

[2] R. Lacroix, R. W. Seifert, and A. Timonina-Farkas, “Benefiting from additive manufacturing for mass customization across the product life cycle,” *Oper. Res. Perspect.*, vol. 8, p. 100201, Jan. 2021, doi: 10.1016/j.orp.2021.100201.

[3] DIN Deutsches Institut für Normung e. V., “Furniture - Strength, durability and safety - Requirements for non-domestic seating; German version EN 16139:2013 + AC:2013.” 2014.

[4] ANSI/BIFMA, “ANSI/BIFMA X5.1-2017(R2022) General-Purpose Office Chairs – Tests.” 2022.

[5] Wilkhahn, “Free to move, Opportunities for new ergonomics in digitalised offices.” Accessed: Jan. 13, 2023. [Online]. Available: https://www.wilkhahn.com/en/office-for-motion/free-to-move

[6] F. Hong, “Open5x: Accessible 5-axis 3D printing and conformal slicing.” Accessed: Nov. 08, 2023. [Online]. Available: https://freddiehong.com/2022/02/28/open5x-accessible-5-axis-3d-printing-and-conformal-slicing/

[7] V. Soler, G. Retsin, and M. Jimenez Garcia, “A Generalized Approach to Non-Layered Fused Filament Fabrication,” presented at the ACADIA 2017: Disciplines and Disruption, Cambridge (Massachusetts), USA, 2017, pp. 562–571. doi: 10.52842/conf.acadia.2017.562.

[8] P. Nicholas, G. Rossi, E. Williams, M. Bennett, and T. Schork, “Integrating real-time multi-resolution scanning and machine learning for Conformal Robotic 3D Printing in Architecture,” *Int. J. Archit. Comput.*, vol. 18, p. 147807712094820, Aug. 2020, doi: 10.1177/1478077120948203.

[9] C. A. Battaglia, M. F. Miller, and S. Zivkovic, “Sub-Additive 3D Printing of Optimized Double Curved Concrete Lattice Structures,” in *Robotic Fabrication in Architecture, Art and Design 2018*, J. Willmann, P. Block, M. Hutter, K. Byrne, and T. Schork, Eds., Cham: Springer International Publishing, 2019, pp. 242–255. doi: 10.1007/978-3-319-92294-2_19.

[10] BRANCH TECHNOLOGY, “Approach: C-Fab.” Accessed: Nov. 08, 2023. [Online]. Available: https://branchtechnology.com/approach/

[11] M. A. Zboinska, “Non-Standard Robotic 3D Printing for Architects - A comprehensive digital fabrication lab pedagogy integrating non-programmable material effects,” in *Pak, B, Wurzer, G and Stouffs, R (eds.), Co-creating the Future: Inclusion in and through Design - Proceedings of the 40th Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe 2022) - Volume 1, Ghent, 13-16 September 2022, pp. 19–28*, CUMINCAD, 2022. Accessed: Nov. 08, 2023. [Online]. Available: https://papers.cumincad.org/cgi-bin/works/paper/ecaade2022_76

[12] A. Shembekar, Y. J. Yoon, A. Kanyuck, and S. Gupta, “Generating Robot Trajectories for Conformal 3D Printing Using Non-Planar Layers,” *J. Comput. Inf. Sci. Eng.*, vol. 19, Mar. 2019, doi: 10.1115/1.4043013.

[13] Y. J. Yoon, M. Yon, S. Jung, and S. Gupta, “Development of Three-Nozzle Extrusion System for Conformal Multi-Resolution 3D Printing With a Robotic Manipulator,” Aug. 2019. doi: 10.1115/DETC2019-98069.

[14] P. Bhatt, A. Kulkarni, R. Malhan,

B. Shah, Y. J. Yoon, and S. Gupta, “Automated Planning for Robotic Multi-Resolution Additive Manufacturing,” *J. Comput. Inf. Sci. Eng.*, vol. 22, pp. 1–18, Aug. 2021, doi: 10.1115/1.4052083.

[15] S. Singamneni, A. Roychoudhury, O. Diegel, and B. Huang, “Modeling and evaluation of curved layer fused deposition,” *J. Mater. Process. Technol.*, vol. 212, pp. 27–35, Jan. 2012, doi: 10.1016/j.jmatprotec.2011.08.001.

[16] A. Alsharhan, T. Centea, and S. Gupta, “Enhancing Mechanical Properties of Thin-Walled Structures Using Non-Planar Extrusion Based Additive Manufacturing,” Jun. 2017, p. V002T01A016. doi: 10.1115/MSEC2017-2978.

[17] Universal Robots, Accessed: Nov. 07, 2023. [Online]. Available: https://www.universal-robots.com/products/ur10-robot/

[18] DYZE DESIGN, “Pulsar^{TM} Pellet Extruder: Industrial High Flow Extruder,” DYZE DESIGN. Accessed: Nov. 07, 2023. [Online]. Available: https://dyzedesign.com/pulsar-pellet-extruder/

[19] J. Rasmussen, “Kevi Kontorstol.” Accessed: Jul. 11, 2023. [Online]. Available: https://www.montanafurniture.com/da-dk/montana/designere/joergen-rasmussen

[20] J. Olivares, *A taxonomy of office chairs: the evolution of the office chair, demonstrated through a catalogue of seminal models and an illustrated taxonomy of their components*. London New York: Phaidon, 2011.

[21] E. Jacobsen, I. B. Nielsen, J. Schjøth-Eskesen, C. H. Fischer, P. B. Larsen, and D. N. Andersen, “Publisher: The Danish Environmental Protection Agency,” 2017.

[22] D. Maga, M. Hiebel, and N. Thonemann, “Life cycle assessment of recycling options for polylactic acid,” *Resour. Conserv. Recycl.*, vol. 149, pp. 86–96, Oct. 2019, doi: 10.1016/j.resconrec.2019.05.018.

[23] F. de Bie, G. G. du Sart, M. Ravard, P. La Scola, and R. Veras, “STAY IN THE CYCLE - RETHINKING RECYCLING WITH PLA BIOPLASTICS [White paper],” TotalEnergies Corbion, 2022. [Online]. Available: https://www.totalenergies-corbion.com/media/xy4a3pcj/stay-in-the-cycle-whitepaper-about-pla-recycling-totalenergies-corbion.pdf

[24] S. Farah, D. G. Anderson, and R. Langer, “Physical and mechanical properties of PLA, and their functions in widespread applications — A comprehensive review,” *Adv. Drug Deliv. Rev.*, vol. 107, pp. 367–392, Dec. 2016, doi: 10.1016/j.addr.2016.06.012.

[25] R. McNeel, “Rhinoceros 3D,” www.rhino3d.com. Accessed: Nov. 09, 2023. [Online]. Available: https://www.rhino3d.com/

[26] “Grasshopper3d.” Accessed: Nov. 09, 2023. [Online]. Available: https://www.grasshopper3d.com/

[27] Pond global, Accessed: Sep. 11, 2023. [Online]. Available: pond.global/