JOURNAL OF DESIGN FOR RESILIENCE
IN ARCHITECTURE & PLANNING

Research Article
Online: www.drarch.org
Volume 5, Issue 3, (314-326), 2024
DOI: 10.47818/DRArch.2024.v5i3134

Clay 3D printing: Exploring the interrelations of materials and techniques

Asena Kumsal Şen Bayram*
Emel Cantürk Akyıldız**

Abstract

This research aims to design an algorithm for optimizing clay 3DP. The algorithm's inputs are defined by combining the results of previous research and specific clay information selected from different regions of Anatolia, utilizing the design of experiment methodology. The design parameters include angle, profile and height; printing parameters include compressor pressure, speed, and layer height; and material parameters are assessed through drop spike, tube pressure, and flow rate tests. Once the inputs and their computation ranges were defined, the algorithm was tested with various inputs and corresponding physical prints to evaluate its recommendation capability. The test prints demonstrated that the printing suggestions made by the algorithm for design, printing and material parameters were suitable for the given parameter inputs. With its current state, the research is not an expert tool for recommendation but a base of a more complex framework for further research.

Keywords: clay 3D printing, clay material, material-parameter interrelation

1. Introduction

Digital fabrication has consistently played a pivotal role in advancing bio-design explorations, where natural intelligence is integrated with embedded digital systems to create innovative and responsive structures. As Zimbarg (2021) highlights, this synergy between the biological and digital realms enables designers and researchers to push the boundaries of what can be achieved in architecture, product design, and ecological systems. At the forefront of these advancements is 3D printing (3DP), widely regarded as a revolutionary technology that can reshape the product development process and the entire manufacturing landscape. According to Gibson et al. (2015), 3DP's transformative impact stems from its ability to streamline production workflows, significantly reduce the material resources needed, and enable the creation of geometrically complex forms that traditional manufacturing methods would struggle to replicate if they could at all.

A key advantage of 3D printing in the context of bio-design is its adaptability. Pressure extrusion systems, in particular, are well-suited for these explorations as they allow for the customization of material matrices, opening up the possibility of working with unconventional materials, including those with irregular properties or textures (Crawford et al., 2022). This flexibility is especially valuable when designing with materials like clay, which poses unique challenges and opportunities for digital fabrication due to its variability and natural composition. Despite its vast potential, clay has not been as thoroughly explored in 3D printing compared to other materials, primarily due to the technical challenges associated with processing it. Issues such as feedstock preparation, sintering conditions, and mechanical weaknesses during and after printing present significant hurdles (Zocca et al., 2015). For example, achieving the correct water-to-clay ratio is critical, as an imbalance can lead to nozzle clogging or structural weaknesses in the printed object. Similarly, external factors like temperature fluctuations or compressor overheating can further exacerbate these challenges, leading to inconsistent print quality and diminishing the overall reliability and strength of the final product.

*(Corresponding author) Assist. Prof. Dr., Maltepe University, Türkiye asenakumsalsenbayram@maltepe.edu.tr
**Assoc. Prof. Dr., Mimar Sinan Fine Arts University, Türkiye emel.canturk@msgsu.edu.tr
Article history: Received 04 October 2024, Accepted 08 December 2024, Published 29 December 2024

Nevertheless, the versatility and sustainability of clay are attracting growing interest, especially in the realm of bio-composite integration within the built environment. One of clay's most compelling features is its hygroscopic nature, which allows it to absorb and release moisture—a property that becomes particularly advantageous when designing for environments that require natural regulation of humidity and temperature. As Dudukovic et al. (2021) point out, unglazed clay can function as a conduit for distributing moisture and nutrients throughout a structure, thanks to its capacity for liquid capillary flow. This characteristic opens up various possibilities for designers, architects, and engineers, ranging from load-bearing structural elements to more delicate applications like tiles, screens, and self-supporting 3D-printed products. Using clay in this way supports innovative design approaches and fosters the development of sustainable architectural solutions that are responsive to their environments (Ramirez-Figueroa & Beckett, 2020).

One of the most intriguing aspects of working with clay in digital fabrication is the material's inherent ability to introduce an experiential, tactile dimension into the design process. Unlike more uniform synthetic materials, clay's organic composition interacts with digital fabrication in unpredictable ways, meaning that designers often need to adjust and respond to the material as they work. This interaction creates a non-linear process, where a predictable, step-by-step design path is often impossible to follow. Instead, iterative testing and constant refinement are required to achieve the desired outcome (Crawford et al., 2022). Designing for clay 3DP, therefore, involves balancing the precision of digital tools with the unpredictability of the material itself. It's a process that requires continuous experimentation, adaptation, and hands-on involvement. This research sought to address key questions surrounding the refinement of this multi-layered process. Specifically, it explored how the workflow for clay 3D printing could be made more precise, how this environmentally friendly material could be made more accessible for designers, and whether a simple, intuitive tool could be developed to facilitate the process for a wider audience.

With these goals in mind, the paper aims to provide practical insights and recommendations for optimizing clay 3DP workflows. Through a combination of theoretical exploration and hands-on experimentation, the research outlines a methodology for improving the quality and consistency of printed clay objects. The iterative testing process employed in this study allowed for fine-tuning various parameters, including material consistency, extrusion pressure, and environmental conditions, all critical to ensuring a successful print. As a result of these experiments, an algorithm for clay 3DP settings has been proposed. This algorithm represents a significant step forward in the field, as it is designed to analyze input parameters—such as material properties, environmental factors, and user preferences—and generate an optimized set of printing values as output. By doing so, the algorithm simplifies the decision-making process for users, enabling them to achieve more reliable and accurate prints with minimal trial and error.

What sets this algorithm apart is its adaptive nature. It includes feedback mechanisms that allow it to learn from previous prints, adjusting its recommendations over time based on empirical data and user input. This continuous improvement ensures the algorithm remains relevant and practical, even as the user's needs evolve or new materials are introduced into the workflow. By incorporating this dynamic feedback loop, the algorithm enhances the immediate print quality and contributes to the long-term development of clay 3DP as a viable manufacturing technology. This could pave the way for a new generation of clay-based designs, from large-scale architectural components to intricate, personalized objects.

In conclusion, while there are still significant challenges to overcome in the realm of clay 3DP—such as improving the material's strength, addressing environmental sensitivities, and refining the precision of the printing process—the potential for innovation is immense. As more research is conducted and tools like the proposed algorithm become more sophisticated, clay will likely emerge as a key material in sustainable design and construction. By combining the timeless qualities of this natural material with cutting-edge digital fabrication techniques, designers and researchers can create a new paradigm for environmentally friendly, intelligent design solutions.

2. Literature Review

This research builds upon previous studies that have applied testing and optimization techniques to improve the performance of clay 3DP processes. Many of these studies have aimed to refine specific process parameters, such as material composition, extrusion speed, or layer height, to address the unique challenges posed by clay as a 3D printing material. For example, Revelo and Colorado (2018) conducted an in-depth analysis of the structural properties of 3D-printed objects made from kaolin clay. By evaluating compression strength, thermal stability, and density (particularly the water-to-clay ratio), they sought to optimize the production process to enhance the mechanical properties and print quality of the final products. Their research helped to highlight how sensitive clay's performance in 3DP is to material composition and print settings.

Similarly, Gürsoy (2018) approached the optimization process by systematically varying speed, layer height, and nozzle settings during the clay 3DP process. Using a consistent cylindrical 3D model, he explored how these parameters influenced print quality, revealing insights into how changes in each variable could affect the printed object's overall strength, resolution, and aesthetic. Guo et al. (2019) took a different approach by focusing on the internal mechanics of the 3DP process, conducting simulations to assess the impact of pressure distribution, shear rate, and velocity within the extruder. These simulations were aimed at identifying the optimal parameters for screw extrusion and direct writing, two techniques used for printing viscous materials such as clay. The study provided valuable data on how internal forces within the extruder could affect material flow and print quality.

Wang et al. (2020) advanced the study of clay 3DP by investigating how the extrusion process affects material behavior. They focused on several key factors—printability, geometrical accuracy, and mechanical performance—and examined how variables like filament profile, layer height, nozzle diameter, and movement speed influenced these outcomes. Their tests revealed essential relationships between these parameters, such as how altering the velocity ratio could affect the consistency of material flow and how the printing-path strategy could either enhance or detract from the final print's dimensional accuracy. Similarly, Cruz et al. (2020) examined the effect of extrusion parameters on the mechanical properties of printed clay geometries, with a particular focus on how changes in these parameters influenced curved and straight profiles with diverging angles. Their research provided insights into how geometric complexity could be managed in clay 3DP, paving the way for more intricate designs and functional architectural components.

Keep (2020a) contributed a practical dimension to the study of clay 3DP through a guide that outlined several hands-on testing methods. His work stands out for its detailed examination of parameters such as drop spike assessments, syringe pressure extrusion, tube pressure, and flow rate, offering practical solutions to common challenges in clay 3DP. His experiments covered various geometries and provided a real-world framework for understanding how specific parameter changes affect the outcome.

In addition to these studies, Farahbakhsh et al. (2022) explored three specific parameters—nozzle-to-substrate distance, delay time, and the distance between nodes and printing paths—to optimize the interlayer bonding strength in ceramic structures. Their work provided insights into how these parameters could be fine-tuned to improve the structural integrity of 3D-printed clay objects. Meanwhile, Lin et al. (2023) used advanced simulation software to model the stress state of the extruder during ceramic 3DP, focusing on key variables such as inlet pressure, moisture content, extruder length, and cone angle. They emphasized the importance of balancing printing speed to avoid defects like blockages or breakpoints, and their simulations helped to identify primary and secondary factors affecting print quality.

Asaf et al. (2023) approached clay 3DP from a materials science perspective, developing a method for transforming soils into a flowable mixture with post-deposition stability. Their experiments, which involved testing 12 different sand and clay mixtures, provided insights into how linear correlations between various properties could inform the optimization of the 3DP process.

Their work culminated in an in-situ cylinder printing test, further validating their method's effectiveness. Wang et al. (2024) focused on the optimization of process parameters for alumina ink in Direct Ink Writing (DIW) 3DP, investigating factors such as filling ratio, nozzle diameter, and layer thickness. Their research provided a deeper understanding of how these variables influence the printability and mechanical performance of alumina-based materials, which share similar challenges with clay 3DP. Finally, Yousaf et al. (2024) conducted a comprehensive study to optimize nozzle diameter, layer height, infill percentage, and printing speed for commercial clay. Their quantitative analysis, which compared measured dimensions to the intended design, helped to assess dimensional accuracy and buildability, offering valuable data on the structural integrity of 3D-printed clay objects.

3. Methods and Materials

This research is centered on designing an algorithm to optimise the 3D printing (3DP) of clay, a material with significant potential in digital fabrication but also presenting considerable challenges. The optimization process in this study is structured around the Design of Experiments (DOE) methodology. DOE is a systematic approach that involves the careful planning, execution, analysis, and interpretation of controlled tests. These tests are designed to evaluate the impact of various factors on a specific outcome, thereby facilitating the identification of optimal process parameters (Durakovic, 2017; Al Rashid et al., 2022; Al Rashid et al., 2024). In this context, the goal is to determine the best values for key parameters within the algorithm to enhance the overall quality, efficiency, and reliability of clay 3DP.

3.1. Parameter and Sub-parameter Definition

Drawing from the literature review studies, this research identifies three primary categories of parameters crucial for optimizing clay 3DP: design, printing properties and material behavior (Table 1). These categories form the basis of the research's focus on the ease-of-use analysis, one of the core objectives of the study. Within each category, specific subcategories are identified to streamline the optimization process.

Table 1 Selected Parameters and Their Subcategories for the Algorithm

Parameter type	Sub parameters
Design	Angle
	Profile type
	Height
Printing	Pressure
	Speed
	Layer height
Material	Drop spike
	Flow rate

For design parameters, the critical variables are the angle, profile type (in line with Cruz et al., 2020), and height (similar to Yousaf et al., 2024). Users are asked to define these parameters by providing an approximate angle value, selecting the profile type (straight or curved), and specifying the maximum height of the design. These design parameters directly affect the structural complexity and aesthetic outcomes of the printed object.

Printing parameters, on the other hand, include compressor pressure (similar to Revelo & Colorado, 2018; Lin et al., 2023), speed (as seen in Gürsoy, 2018; Wang et al., 2020), and layer height (referenced by Wang et al., 2020; Yousaf et al., 2024). These variables are essential for controlling the material flow and ensuring the accuracy of each printed layer. However, the capabilities of the clay printer used in this research impose certain limitations on these parameters, mainly due to the screw-controlled material flow system (Figure 1).

Delta LDM 3DP	
Printing area	Ø:300 mm h:400 mm
Nozzle size	1.5mm
Layer height	1 - 2mm
Extruder	Screw controlled
Tank size	Ø:100 mm – h:400 mm

Figure 1 The clay 3DP was used in this research

The reviewed articles emphasize the importance of chemical compositions and complex lab tests to analyze the properties of clays used in 3D printing. These studies often rely on data derived from intricate laboratory results, providing valuable insights into how different clay types respond to various printing processes. However, replicating such lab-based evaluations can be quite challenging for many users—particularly novice practitioners or those with limited access to advanced testing equipment. The expertise, time, and resources required to perform chemical analysis or advanced testing methods could act as significant barriers to entry, especially for individuals or small-scale operations looking to experiment with clay 3DP.

To address these challenges and ensure inclusivity, this research adopts more accessible and practical methods for evaluating material behavior. The aim is to enable a broader range of users, regardless of their technical background or available resources, to contribute meaningfully to optimizing clay 3DP. Therefore, more straightforward, approachable testing techniques are incorporated into the research scope, balancing precision and practicality while yielding reliable data for the algorithm's calculations. These methods make it easier for users to gather material behavior parameters without requiring extensive lab infrastructure.

The material behavior parameters selected for this study include drop spike test results, tube pressure measurements, and flow rate assessments (similar to Keep, 2020b). These tests are designed to be easy to conduct while providing sufficient information to inform the optimization algorithm.

Drop Spike Test: In this test, a standardized tool or weight is dropped from a fixed height onto the clay sample, and the indentation depth created by the impact is measured. This method helps assess the consistency and stiffness of the clay. The deeper the indentation, the softer and more pliable the clay is, indicating a higher water content or a less compacted material. Conversely, a shallower indentation would suggest a denser or drier clay sample. This simple test indicates the clay's workability, which is critical in ensuring smooth extrusion during 3D printing.

Tube Pressure and Flow Rate Test: A container is filled with each clay sample, and controlled pressure is applied to the material. The clay is then forced through an attached plastic tube, and the flow rate of the clay is measured as it exits the tube. This test simulates the extrusion process used in 3DP and helps evaluate how easily the clay can flow under pressure, which is crucial for determining its printability. If the flow rate is too slow, the material may clog the nozzle or lead to inconsistencies in the printed layers. If the flow rate is too fast, the clay may not retain its shape once extruded, leading to deformation in the final print. Users can gauge the optimal pressure and material consistency needed for successful 3D printing by measuring the flow rate.

These tests are selected not only for their simplicity but also for their ability to provide actionable data. Novice users can efficiently perform these evaluations with basic tools, yet the results offer valuable insights into the clay's behavior during printing. This approach ensures that the research remains accessible to a broad audience while offering a robust framework for optimizing clay 3DP workflows. By focusing on tests that can be conducted with minimal technical expertise, the research encourages broader participation in the field, fostering innovation and experimentation across various levels of experience.

In addition, these approachable methods also help mitigate some of the inconsistencies that can arise when using natural materials like clay, which often vary in composition even within the same type. Using these simplified tests to assess material behavior on a case-by-case basis, users can adjust their printing parameters to suit the specific properties of the clay they are working with. This flexibility allows for more reliable results in real-world applications, ensuring that even novice users can achieve high-quality prints without conducting complex chemical analyses.

Ultimately, including these practical testing methods aligns with the overarching goals of this research—to democratize access to clay 3DP optimization tools and provide users of all skill levels with the resources they need to succeed. These methods not only simplify the process of gathering critical material behavior data but also help ensure that the resulting algorithm remains adaptable to a wide variety of use cases, from hobbyist projects to more advanced industrial applications.

3.2. Material Selection

The algorithm's computational capability is intricately tied to both the limitations of the machinery used and the type of clay employed during the 3D printing process. This relationship underscores the need for an in-depth understanding of the properties and behaviors of the materials involved. While previous studies (such as Keep, 2020b) have provided valuable material information that contributed to the development of this algorithm, further analysis was essential to tailor the tool to the specific types of clay utilized in this research. Consequently, in addition to leveraging existing data from the literature, the behaviors of three distinct clays sourced from Anatolia were analyzed to ensure the algorithm's effectiveness and applicability.

The clays chosen for this study were sourced from three different regions of Turkey, each characterized by unique climatic and geographical features. These variations in environmental conditions contribute to the distinct mineral compositions and physical properties of the clays, which can significantly influence their behavior in 3D printing processes. The selected clays include samples from Adana in the Mediterranean Region, Avanos in the Central Anatolia Region, and Menemen in the Aegean Region. Each region is known for its rich clay deposits, which are traditionally used in pottery and other ceramics, making them ideal candidates for exploration in modern clay 3DP.

A detailed comparison of their mineral compositions was conducted to understand these clays' differences comprehensively. This was achieved using XRF (X-ray fluorescence) analysis, a widely recognized and reliable method for determining the elemental makeup of various materials. XRF has long been used in material science and geology to analyze the chemical composition of soils, minerals, and other substances, offering a non-destructive way to identify key elements of the material. This technique identified each clay sample's specific mineral components, allowing for a more nuanced understanding of how these elements might impact the 3D printing process, such as their influence on extrusion behavior, drying time, or sintering properties (Abdulli, 2023).

The mineral compositions of the Adana, Avanos, and Menemen clays were analyzed and summarized in Table 2, providing a clear visual representation of the elemental differences between these samples. The XRF analysis revealed significant variation in the presence of certain minerals, such as silica, alumina, and iron oxide, which are known to affect the structural integrity and behavior of clays during printing. For instance, a higher silica content generally enhances the material's heat resistance and strength after firing, while variations in iron oxide can influence the clay's color and plasticity. These differences are crucial for determining how well a clay will perform in the 3DP process, from extrusion to final sintering.

The clay from Adana, located in Turkey's Mediterranean region, is characterized by its relatively warm climate and fertile soil. The XRF analysis indicated that this clay has a balanced composition, with moderate levels of silica and alumina, making it versatile for various types of 3D printing applications. However, its mineral composition suggests it may require specific adjustments to nozzle settings and extrusion pressure to achieve optimal flow during printing.

Avanos, situated in Central Anatolia, is renowned for its pottery tradition, with clay shaped by centuries of erosion from volcanic rocks in the region. The XRF analysis of Avanos clay revealed higher levels of iron oxide, which could affect the clay's plasticity and workability during 3D printing. This increased plasticity could be advantageous, making the material easier to shape but potentially more prone to deformation if not carefully controlled. The algorithm considers these unique properties, suggesting specific pressure settings and layer heights tailored to the Avanos clay.

The clay from Menemen, in the Aegean Region, displayed a higher silica content, which enhances its durability and heat resistance. This property makes Menemen clay an excellent candidate for more structurally demanding 3D printed applications, such as load-bearing components or architectural elements. However, the increased silica content may also lead to a stiffer material, requiring careful extrusion speed and nozzle diameter adjustments to ensure a smooth printing process without clogging or inconsistencies.

By integrating the results of the XRF analysis into the algorithm, the tool can make more accurate predictions and recommendations for each type of clay, adjusting parameters like extrusion speed, layer height, and nozzle diameter accordingly. This approach optimises the clay's performance during printing and ensures that the final printed objects meet the desired structural and aesthetic standards.

The regional variations in clay composition underscore the complexity of working with natural materials in digital fabrication. Unlike synthetic materials, which can be engineered for uniformity, natural clays exhibit significant variability even within the same type or geographical area. This variability necessitates a flexible and adaptive approach to 3D printing, where the printing parameters must be adjusted based on the specific properties of each batch of clay. The algorithm developed in this research incorporates these considerations, offering a more tailored solution that considers the nuances of working with diverse clays from different regions.

Table 2 XPF Analysis of Adana, Avanos and Menemen Clays (Gathered from Abdulli, 2023)

	Fe2O3	**CaO**	**SiO2**	**K2O**	**Cl**	**CuO**	**TiO2**	**SO3**	**MnO**	**Al2O3**
Adana	13.83	24.5	31.31	2.01	0	0.07	0.98	0.65	0.17	8.35
Avanos	15.18	9.03	42.42	5.09	0	0.07	1.48	0	0.17	17.23
Menemen	16.89	4.52	44.96	5.11	0	0.07	1.58	0	0.08	19.46

The XRF analysis of the selected clays from Adana, Avanos, and Menemen provides a solid foundation for the algorithm's ability to optimize clay 3DP workflows. By understanding the elemental compositions of these clays, the algorithm can make informed recommendations, ensuring that each type of clay is used to its fullest potential. This tailored approach not only enhances the precision and quality of the printed objects but also expands the versatility and usability of the algorithm across different types of clay and 3DP applications.

When the table is examined, the high SiO2 and Al2O3 content commonly detected in all materials indicates the materials' high fire resistance and structural integrity capacity. The CaO content, detected predominantly in Adana clay, can improve the hardening and adhesion properties of the material but may also cause deformations and cracks. The Fe2O3 content, observed in similar proportions in all materials, plays a significant role in the colouring of the material. The presence of other components such as K2O, TiO2, MnO, and SO3 has minimal impact on the physical and chemical properties of the materials. For example, K2O can affect the fusion temperature in ceramics, while TiO2 can provide pigmentation properties. The deficient levels of CuO and CI indicate that these elements will not significantly affect the overall properties of the materials (Abdulli, 2024).

As previously mentioned, since the research aimed to create an algorithm that everyone can easily use, simple test results that do not require access to laboratory results, as discussed above, were used as inputs. The drop spike and flow rate test results conducted on samples were believed to have the appropriate consistency for the machine's usage, supporting the materials' laboratory results (Table 3).

Table 3 Drop Spike and Flow Rate Tests of Selected Clay Types

	Spike depth(cm)	Tube flow (cm/10sec)	Pressure (bar)
Adana	2.5	2	8
Avanos	3	4	8
Menemen	3	6	8

3.3. Algorithm Framework

By adapting and transforming the detailed examination of Cruz et al. (2020), printing trials with straight and curved sections at 30, 45, and 60 degrees were conducted for each clay to gather the information used in the algorithm's suggestion calculations. Due to the necessity of obtaining height data where the prints progress smoothly from the trials, the prints were observed, and printing was stopped at the height where issues occurred. The print speed and flow rate were kept at 100% during the trials, while the layer height was set to 1mm for all prints. The results showed that hard materials reached lower heights in straight sections (Figure 2). The data obtained from the tests are supported by studies from the literature where the same data could be obtained, allowing for the development of the algorithm's computational technique and the creation of a recommendation process.

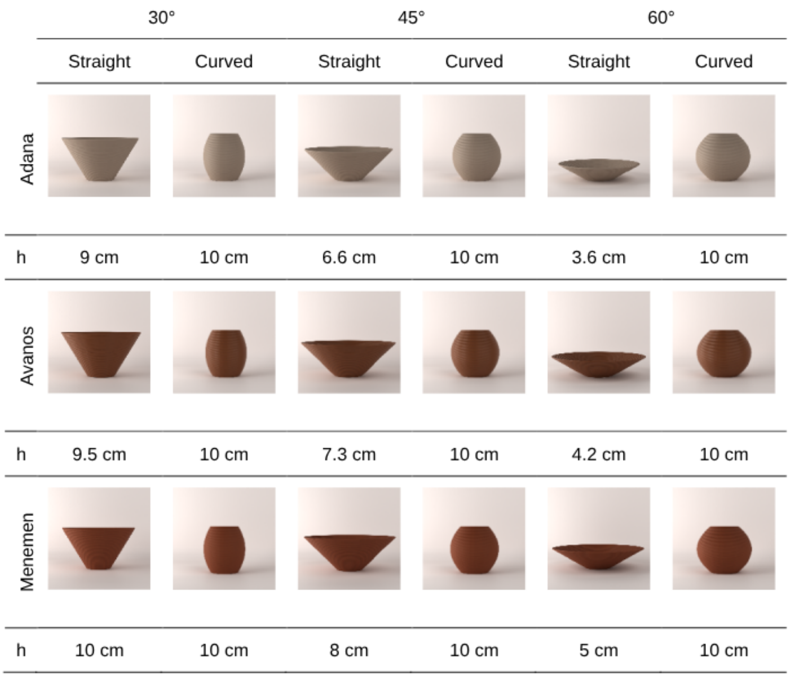

Figure 2 Clay-printed examples with changing section, angle and height values

The primary objective of this research is to develop an algorithm capable of providing recommendations for missing inputs based on the given design specifications, printing configurations, and material properties. By inputting data from at least two of these three parameter groups, recommendations for the third parameter are developed using the Python tool in Rhino 3D's Grasshopper interface. Grasshopper is the graphic interface to design algorithms. The Phyton tool of that interface allows users to embed their code for operations directly for desired calculations. Although the researchers of this paper are architects without coding knowledge, today, with the improvements in artificial intelligence (AI) tools, it is easy to have Phyton codes with the help of AI tools. Therefore, ChatGPT, an advanced AI-powered conversational assistant developed by OpenAI, was asked to write a Phyton code for Grasshopper that can turn defined inputs through pre-defined rule sets. The gathered code was then re-designed with the pre-defined parameters to make the desired suggestions for the final algorithm (Figure 3).

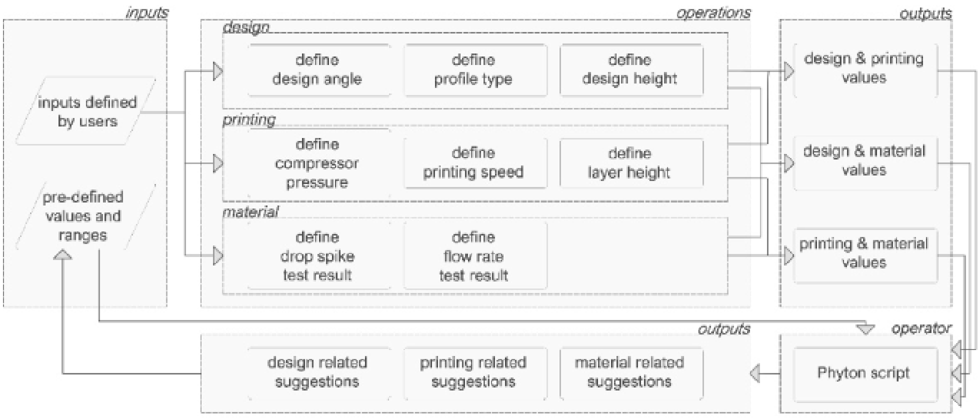

Figure 3 Algorithm flowchart

4. Results and Findings

The algorithm underwent meticulous and comprehensive testing across three applications involving different input values and clay types. This rigorous approach was designed to ensure the algorithm's effectiveness in generating precise recommendations within suitable ranges, fostering confidence in its reliability and practicality.

4.1. Test 1: Printing Parameter Suggestions

The design and material inputs were entered in the first test to gather recommendations for printing parameters. The angle parameter was set at 50 degrees—situated between previously tested ranges of 30–45 and 60 degrees—to assess the algorithm's decision-making in a new range. A height of 10 cm and a curved profile type were selected to create a standard testing condition. The material properties were defined to mimic Menemen clay, with a drop spike value of 3 and a flow rate of 6, ensuring alignment with its printing requirements.

The algorithm output pressure values of <8, a speed of 100, and a layer height of <1, which were well-suited for Menemen clay. A prototype was printed using these parameters to validate the algorithm's predictions, confirming the accuracy of the results (Figure 4).

4.2. Test 2: Design Parameter Suggestions

Material and printing inputs were provided in the second test to obtain design parameter suggestions. For material testing, none of the selected clays had a flow rate 1, allowing the test to evaluate the algorithm's behavior under low flow rate conditions. Printing parameters were kept consistent with the previous test (pressure: 8, speed: 100, layer height: 1) to analyze the algorithm's ability to adapt its design recommendations.

The algorithm suggested a design angle between 30–45 degrees, a straight profile type, and a height of <4 cm. These outputs closely aligned with the properties of Adana clay. A prototype was printed using this clay type, further validating the algorithm's reliability (Figure 4).

4.3. Test 3: Material Parameter Suggestions

The third test assessed the algorithm's capability to suggest material parameters based on specific design and printing inputs. With prior trials using angles of 30–45 and 60 degrees, the angle was again set at 50 degrees to observe the algorithm's recommendations at higher values. Recognizing the challenges of printing at steeper angles with straight profiles, the height was limited to 4 cm. Printing parameters included a low-pressure input of 6, chosen to test the algorithm's ability to suggest materials akin to Avanos clay, which performs well under low-pressure conditions.

As anticipated, the algorithm proposed drop spike values >3 and flow rates >6, consistent with the properties of Avanos clay. A prototype printed using these outputs confirmed the accuracy and suitability of the algorithm's recommendations (Figure 4).

The results of these test prints unequivocally demonstrated the algorithm's reliability across all tested scenarios. Its ability to provide accurate suggestions for design, printing, and material parameters underscores its versatility and adaptability to various clay types and conditions. Including different clay types during testing was particularly noteworthy, showcasing the algorithm's potential to optimize the 3D clay printing process. By offering precise, reliable, and practical guidance, the algorithm supports achieving desired outcomes across a wide range of specified parameters, further validating its application for diverse material variations.

		Test 1		Test 2		Test 3	
		inputs	outputs	inputs	outputs	inputs	outputs
Design	Angle	50			30-45	65	
	Profile type	curved		straight		straight	
	Height	10			<4	4	
Printing	Pressure		<8	8		6	
	Speed		100	100		100	
	Layer height		<1	1		1	
Mat.	Drop spike	3		2			>3
	Flow rate	6		1			>6
Printed results							

Figure 4 Test results of the algorithm with various input types

5. Discussion

Based on the comprehensive trials conducted under various parameters, it is clear that the optimization algorithm designed to provide 3D printing (3DP) recommendations for clay-based materials has successfully achieved its primary objective. Although promising, the results of these tests also revealed several technical challenges that need to be addressed for future improvements. One of the most significant challenges is the limitation posed by the algorithm's reliance on the computational module. This module depends heavily on data drawn from existing literature and results obtained from real-time testing. While this data provides a solid foundation, it does restrict the algorithm's flexibility and scalability. The performance and accuracy of the algorithm are bound by the availability and quality of the data, which may only sometimes be sufficient for more complex or diverse printing scenarios.

Moreover, a critical obstacle encountered during the testing phase is the inherent variability in the properties of clay, even when working with the same type of material. Clay, a naturally sourced material, is subject to inconsistencies in composition, moisture content, and texture, all of which can lead to fluctuations in print quality. These variances make it difficult to maintain uniformity across prints, as subtle differences in the material's behavior can result in inconsistent outputs. Therefore, addressing this issue of material uniformity is essential for enhancing the reliability and predictability of the 3D printing process.

Another limitation identified is related to the clay printer used throughout the research. Although this particular printer has been sufficient for the early stages of experimentation, it needs more versatility to handle a broader range of clay types optimally. Fortunately, ongoing research is being conducted with a more advanced clay printer, capable of printing with a wider array of materials and offering improved precision. This opens the door to more complex and nuanced studies and emphasizes the importance of equipment quality in achieving consistent results. While this study provides valuable insights, it is apparent that more sophisticated hardware will be necessary to fully realize the algorithm's potential.

Environmental factors also posed significant challenges during the experimentation process. The sensitivity of the 3D printing equipment to external conditions, such as fluctuations in temperature and humidity, proved to be a substantial barrier to reproducibility. Variations in these environmental factors led to inconsistent print outcomes, particularly in terms of layer adhesion and material curing times. While the physical conditions of the laboratory were controlled to some extent, the unpredictable nature of sunlight exposure, temperature shifts, and humidity changes had a noticeable impact on print quality. Though manageable in a controlled single study, these environmental influences must be minimized for more rigorous and long-term testing. To ensure the algorithm's accuracy, future experiments should be conducted in environments where temperature and humidity can be strictly regulated to prevent interference with printing.

Another aspect that emerged during the testing was the algorithm's computational demands. The algorithm's required data processing complexity means that real-time feedback is often delayed, hindering practical, real-world applications. For this tool to be effective in professional 3D printing settings, the algorithm's processing speed must be optimized for instantaneous adjustments and recommendations. Any significant lag in feedback could disrupt the flow of the printing process, leading to errors that may not be immediately correctable. Therefore, optimizing the algorithm for real-time use is one of the most pressing challenges.

The next phase of this research will involve a deeper dive into fine-tuning the algorithm's parameters. This will include extensive testing with various clay types, encompassing different compositions, textures, and moisture contents, to further refine the algorithm's predictive accuracy. By experimenting with a broader range of printing conditions, the research team aims to develop a more robust model capable of handling clay materials' diverse and unpredictable nature. This exploration will provide a more comprehensive understanding of how various factors influence print quality and how the algorithm can adapt to different scenarios.

Aside from technical refinement, another crucial step in this research will be the collection of user feedback. We are committed to engaging with diverse users, from professionals to hobbyists, to identify any practical issues that might arise when the algorithm is used in real-world applications. This feedback will be invaluable in making user-centered improvements, ensuring that the tool remains intuitive and responsive to the needs of its audience.

To complement these advancements, developing a comprehensive user manual and training program will be essential. This will include creating detailed documentation that outlines every aspect of the algorithm's operation, from its initial setup to more advanced troubleshooting tips. Interactive tutorials, incorporating video demonstrations and step-by-step guides, will also be developed to assist users in navigating the software effectively. By providing clear and accessible instructions, the research team hopes to make the algorithm widely adoptable, even for individuals with limited technical expertise.

In terms of future improvements, there are several promising avenues for enhancing the algorithm's functionality. Expanding the database of clay types and material properties database would allow the algorithm to generate even more precise recommendations tailored to a broader array of materials. Additionally, integrating machine learning techniques could enable the algorithm to learn from each print, continuously improving its performance by analyzing past results and adjusting its recommendations accordingly. This adaptive capability would make the tool not only more accurate but also more efficient over time. Moreover, incorporating a user-friendly interface with real-time visualization and feedback features would make the algorithm more accessible to a broader range of users, ensuring that experts and beginners can take full advantage of its capabilities.

In conclusion, while this study has demonstrated the potential of the optimization algorithm for clay 3D printing, there remains significant room for development. Addressing the challenges of material variability, environmental sensitivity, computational demands, and user engagement will be critical in ensuring the algorithm's long-term success and applicability across various industries. By continuing to refine the tool and expand its capabilities, this research has the potential to revolutionize the field of 3D printing with clay, paving the way for more reliable, efficient, and user-friendly solutions.

Acknowledgements

We especially want to thank İnana Abdulli (2023) for sharing and allowing the use of her unpublished laboratory results for this research. In addition, [Omitted for blind review] and [Omitted for blind review] made a great effort to gather and send the clay samples of Adana, which requires excellent thanks and appreciation. During the fabrication trials and image preparations, the voluntary help [Omitted for blind review] was a lifesaver, and the whole process would have been much more challenging.

References

Abdulli, İ. (2023). Getirilen Numuneye Yönelik Rapor, rapor no: *46232573*, *Çukurova Üniversitesi Mühendislik Fakültesi Maden Mühendisliği Bölümü*, unpublished report.

Abdulli, İ. (2024). *Sürdürülebilirlik bağlamında yerel kilin yapı malzemesi olarak dijital fabrikasyon süreci: Adana boşluklu tuğla örneği* / Unpublished Master's Thesis, Çukurova University.

Al Rashid, A., Abdul Qadir, S., & Koç, M. (2022). Microscopic analysis on dimensional capability of fused filament fabrication three-dimensional printing process. *Journal of Elastomers & Plastics*, *54*(2), 385-403. https://doi.org/10.1177/00952443211047263

Al Rashid, A., Abdul Qadir, S., & Koç, M. (2024). Life cycle assessment on fabrication and characterization techniques for additively manufactured polymers and polymer composites. *Cleaner Environmental Systems*, *12*(2024). https://doi.org/10.1016/j.cesys.2023.100159

Asaf, O., Bentur, A., Larianovsky, P., & Sprecher, A. (2023). From soil to printed structures: A systematic approach to designing clay-based materials for 3D printing in construction and architecture. *Construction and Building Materials*, *408*(2023), 133783. https://doi.org/10.1016/j.conbuildmat.2023.133783

Boyer, S. A. E., Jandet, L., & Burr, A. (2021). 3D-extrusion manufacturing of a kaolinite dough taken in its pristine state. *Frontiers in Materials*, *8*(2021). https://doi.org/10.3389/fmats.2021.582885

Chaari, M. Z., Abdelfatah, M., & Loreno, C. (2022). A trial to convert a polymer FDM 3D printer to handle clay materials. *SN Applied Sciences*, *4*(2022) 1-11. https://doi.org/10.1007/s42452-022-04937-w

Crawford, A., In-na, P., Caldwell, G., Armstrong, R., & Bridgens, B. (2022). Clay 3D printing as a bio-design research tool: development of photosynthetic living building components. *Architectural Science Review*, *65*(3), 185-195. https://doi.org/10.1080/00038628.2022.2058908

Cruz, P. J. S., Camões, A., Figueired, B., Ribeiro, M. J., & Renault, J. (2020). Additive manufacturing effect on the mechanical behaviour of architectural stoneware bricks. *Construction and Building Materials*, 238 (2020). https://doi.org/10.1016/j.conbuildmat.2019.117690

Dudukovic, N. A., Fong, E. J., Gemeda, H. B., Deotte, J. R., Cerón, M. R., Moran, B. D., Davis, J. T., Baker, S. E., & Duoss, E. B. (2021). Cellular fluidics. *Nature*, *595*, 58-65. https://doi.org/10.1038/s41586-021-03603-2

Durakovic, B. (2017). Design of experiments application, concepts, examples: State of the art. *Periodicals of Engineering and Natural Sciences*, *5*(3), 421-439. https://doi.org/10.21533/PEN.V5I3.145

Farahbakhsh, M., Rybkowski, Z. K., Zakira, U., Kalantar, N., & Onifade, I. (2022). Impact of robotic 3D printing process parameters on interlayer bond strength. *Automation in Construction*, *142* (2022). https://doi.org/10.1016/j.autcon.2022.104478

Gibson, I., Rosen, D., & Stucker, B. (2015). Additive manufacturing technologies: 3D printing, Rapid (Second ed.). *Springer*.

Guo, C. F., Zhang, M., & Bhandari, B. (2019). A comparative study between syringe-based and screw-based 3D food printers by computational simulation, Comput. *Electron Agric*. *162*(2019) 397-404. https://doi.org/10.1016/j.compag.2019.04.032

Gürsoy, B. (2018). From control to uncertainty in 3D printing with clay. In A. Kępczyńska-Walczak & S. Białkowski (Eds.), *Proceedings of of the 36th International Conference on Education and Research in Computer Aided Architectural Design in Europe: Computing for a better tomorrow*, Volume *2*. (pp. 21-30). eCAADe and Faculty of Civil Engineering, Architecture and Environmental Engineering, Lodz University of Technology.

Keep, J. (2020a) A guide to clay 3D printing. http://keepart.co.uk/Journal/JK_Guide_to_Clay_3D_Printing.pdf. Retrieved at 21.05.2024

Keep, J. (2020b) Testing of six clays for extrusion 3D printing. https://keepart.co.uk/Journal/Test_Six%20Clays.pdf. Retrieved at 21.05.2024

Lin, T., Zhao, Z., Wang, T., & Pan, Y. T. (2023). Three-dimensional printing of large ceramic products and process simulation. *Materials*, *16*(10), 3815. https://doi.org/10.3390/ma16103815

Peng, E., Zhang, D., & Ding, J. (2018). Ceramic robocasting: recent achievements, potential, and future developments. *Advanced Materials*, *30*(47), 1-14. https://doi.org/10.1002/adma.201802404

Ramirez Figueroa, C., & Beckett, R. (2020). Living with buildings, living with microbes: Probiosis and architecture. *Arq: Architectural Research Quarterly 24*(2): 155 168. https://doi.org/10.1017/S1359135520000202

Ravoor, J., Karuppan, D., & Elsen, S. R. (2023). Binder optimization for extrusion based 3D printing of hydroxyapatite materials using different polymeric binders. *Materials Today: Proceedings*, (2023). https://doi.org/10.1016/J.MATPR.2023.03.107

Revelo, C. F., & Colorado, H. A. (2018). 3D printing of kaolinite clay ceramics using the direct ink writing (DIW) technique. *Ceramics International*, *44*(5), 5673-5682. https://doi.org/10.1016/j.ceramint.2017.12.219

Savage, D. & Liu, J. (2015). Water/clay ratio, clay porosity models and impacts upon clay transformations. *Applied Clay Science*, *116-117*, 16-22. https://doi.org/10.1016/j.clay.2015.08.011

Wang, S., Ping, T. H., Felix, R., & Carlos, B. (2020). Detailing the configuration to perform better clay printing. In D. Holzer, W. Nakapan, A. Globa, I. Koh (Eds.), *RE: Anthropocene, Design in the Age of Humans - Proceedings of the 25th CAADRIA Conference*-Volume *1*, Chulalongkorn University (pp. 153-161) https://doi.org/10.52842/conf.caadria.2020.1.153

Wang, S., Xiang, Y., Feng, H., Cui, Y., Liu, X., Chang, X., Guo, J., & Tu, P. (2024). Optimization of 3D printing parameters for alumina ceramic based on the orthogonal test. *ACS Omega*, *9*(14), 16734–16742. https://doi.org/10.1021/acsomega.4c00819

Yousaf, A., Rashid, A. A., & Koç, M. (2024) Parameter tuning for sustainable 3D printing (3DP) of clay structures. *Journal of Engineering Research*, 2024. https://doi.org/10.1016/j.jer.2024.05.027

Zhou, J., Barati, B., Wu, J., Scherer, D., & Karana, E. (2021). Digital biofabrication to realize the potentials of plant roots for product design. *Bio-Design and Manufacturing*, *4*(1), 111–122. https://doi.org/10.1007/s42242-020-00088-2

Zimbarg, A. (2021). Bio-Design Intelligence. In P. F. Yuan, H. Chai, C. Yan, & N. Leach (Eds.), *Proceedings of the 2021 DigitalFUTURES: The 3rd International Conference on Computational Design and Robotic Fabrication* (pp. 92-101). *Springer*. http://doi.org/10.1007/978-981-16-5983-6_9. Retrieved 22nd March, 2023 from https://von.gov.ng/climate-change-nigeria-moves-to-reduce-carbon-emissions

Zocca, A., Colombo, P., Gomes, C. M. & Günster, J. (2015). Additive manufacturing of ceramics: issues, potentialities, and opportunities. *Journal of the American Ceramic Society*, *98*(7), 1983-2001. https://doi.org/10.1111/jace.13700

Resume

Asena Kumsal Şen Bayram received her BArch degree in Architecture (2007), MSc degree in Architectural Design Program (2009) and PhD degree in Architectural Design Program (2015) at Istanbul Technical University. During her graduate studies, besides her Research and Development projects, she worked on various Architectural design and construction projects as Co-owner, project manager and designer in her R&D company stated in ARITechnopark at Istanbul Technical University. She has been working as a part-time faculty tutor in different universities. Since 2019 she has been working as a full-time faculty member in Faculty of Architecture and Design at Maltepe University. Her current research interests are digital design and fabrication techniques in architecture and design education.

Emel Cantürk Akyıldız is an architect and Assistant Professor at Mimar Sinan Fine Arts University, Faculty of Architecture. She studied architecture at Istanbul Technical University and holds a PhD in Architectural Design from the same university. She taught design studio at the undergraduate and graduate level, architectural representation and theory of architecture between 2013 and 2021 at Maltepe University and between 2021 and 2024 at Kocaeli University. Since February 2024, she has been a faculty member of Mimar Sinan Fine Arts University, Faculty of Architecture. Her research areas are mainly architectural education, architectural design, theory and criticism, emerging AI technologies as a new design method and their transformative impact on design thinking and architectural design education.