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Fused Space in Architecture via Multi-Material 3D Printing Using Recycled Plastic: Design, Fabrication, and Application

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Abstract

The innovation of multi-material offers significant benefits to architectural systems. The fusion of multiple materials, transitioning from one to another in a graded manner, enables the creation of fused space without the need for mechanical connections. Given that plastic is a major contributor to ecological imbalance, this research on fused space aims to recycle plastic and use it as a multi-material for building applications, due to its capacity for being 3D printed and fused with other materials. Furthermore, to generate diverse properties for the fused space, several nature-inspired forming algorithms are employed, including Swarm Behavior, Voronoi, Game of Life, and Shortest Path, to shape the building enclosure. Subsequently, digital analyses, such as daylight analysis, structural analysis, porosity analysis, and openness analysis, are conducted on the enclosure, forming the color mapping digital diagram, which determines the distribution of varying thickness, density, transparency, and flexibility gradation parameters, resulting in spatial diversity. During the fabrication process, Dual Force V1 and Dual Force V2 were developed to successfully print multi-material gradations with fused plastic following an upgrade to the cooling system. Finally, three test sites in London were chosen to implement the fused space concept using multi-material.

Keywords: multi-material; recycled plastic; fused space; 3D printing; robotic fabrication

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1. Introduction

By combining materials with different properties, multi-material achieves high performance and has a significant impact on various aspects of products. Designers are being driven to add more and more functionalities to materials in order to save costs and improve the performance of technical products [1–3]. In order to achieve the objective of climate-neutral buildings and the correspondingly rising expectations on building performance, architecture is becoming more complicated [4,5]. The application of multi-material in architecture can create fused space with continuous property conditions [6]. This method makes it possible for architecture to depart from twentieth-century standard building procedures with component-based assembly. Fused space achieved by the creation of multi-material takes into consideration how architecture can advance from unchanged practice through material fusion [7,8]. In this approach, the pieces, parts, assemblies, components, elements, connections, bolts, screws, and glues used in traditional building are all absent. Instead, there is just topology, enabled by the 3D printing of materials that are fused together continuously, without the need for mechanical or other connections [9].

Fused-space research aims to contribute to waste-based plastic material reuse in architecture [6]. Spaces produced by recycling material can also have a substantial impact on the environment by lowering greenhouse gas emissions and extending the life of buildings [10–12]. How can recycled plastic materials be integrated into architectural design to form structural and functional enclosures? The following research explored two types of recycled plastic, PET and TPU, which are both widely used and recycled. When combined, these polymers produce a fused multi-material and have different properties which can transform from rigid to flexible and from transparent to opaque. Fused space in architecture also aims to create different spatial properties by applying the recycled multi-material with complex mechanical properties inspired by nature and biological concepts [13,14]. In light of this, the research investigated the combination of 3D-printed plastics with different levels of rigidity, opacity, color, and texture to create a wide range of spatial properties.

In addition, fused-space design also pays attention to structural, privacy, and light quality gradations, which can facilitate a variety of functions to serve public needs and demands. The first step of design is to utilize a vacant space as the original bounding box, and fill that space using the sphere packing digital algorithm [15], with each sphere fostering an environment that can support different functions based on light and privacy needs. Then space enclosure between the bounding box and sphere space is carved using the Boolean method. Following this, multiple forming algorithms inspired by nature are applied to shape the carved mass, such as Swarm Behavior [16], Game of Life [17], Voronoi [18], and Shortest Path [19]. After this, digital studies like daylight analysis, structure analysis, porosity analysis, and openness analysis are applied to the formed mass to come up with different gradation parameters such as thickness, density, transparency, and flexibility gradation for the prototype design, which results in creating various space properties.

Multi-material can be integrated since different robotic fabrication techniques can be combined [20]. During the fabrication process of multi-material, these computer-aided design models can be printed through layer-by-layer manufacturing of 3D components based on a digital algorithm [21,22]. To increase efficiency, the printing in this research was performed using a robot with six axes. Model tool paths were transformed into voxels to achieve the lattice structure. During fabrication, the current robotic arm machine was upgraded twice in the laboratory, from Dual Force V1 to Dual Force V2. Dual Force V1 made it possible to print with dual filaments at the same time instead of a single one. Dual Force V2 printed multi-material gradation successfully with the fused PET and TPU after upgrading the cooling system. Based on the fabrication experiment for printing large-scale models, the fused-space design with multi-material was intended to be applied to the real testing sites.

2. Multi-Material Research

2.1. Introduction to Multi-Material

Multi-material refers to the combination of variable materials with significantly different properties, which is a useful tool to discover new applications in the hidden dimension of material existence [23]. Material can easily be reformed, blended, and applied in the digital area. Thus, high-performance multi-material can be created by combining materials with variable properties, such as diverse color, texture, stiffness, insulation, and gradation. There is a great potential in exploring the integration of the architecture industry and the application of multi-material. Through research in recent years, the use of multi-material in architectural systems has seen great benefits not only in cost and energy saving, but also in architectural morphology and creating various properties. For example, the application of multi-material in architecture systems opens up greater possibilities to define new design approaches, and create variable material responses for decoration, aesthetic criteria, construction, and architecture components at the same time [24]. Furthermore, the revolution of multi-material has stimulated the appearance of special, high-performance structural behaviors. A design developed by combining several materials that change from one to another as a gradation without any mechanical connections is known as a fused space. Fused space represents an opportunity to move away from component-based assembly and the standard practices of the twentieth century. The approach being used has a significant effect on the environment by lowering greenhouse gas emissions [10,11,13], and it also has a broader effect on building construction and architecture.

2.2. Recycled Plastic Materials

Fused-space research explores sustainably reusing plastic as construction materials to achieve upcycling [25]. Due to the world's inability to handle the fast-growing output of disposable plastic products, plastic pollution has emerged as one of the most urgent environmental problems. With 215 g of plastic trash produced daily per capita, the UK is a significant contributor to the global plastic catastrophe [26,27]. Waste plastic keeps accumulating in the world, which indicates a potential opportunity to reuse and recycle it. Therefore, this research intends to recycle plastic and use it in the construction industry, because not only is plastic a major contributor to the imbalance of our ecological system, but plastic can also be 3D printed and fused with other materials. Recycling and reusing waste plastic material in the building sector could also have a tremendous impact on the development of a sustainable environment.

There are different types of recyclable plastic, such as HDPE, PET, PVC, PP, and TPU.

This research, which could contribute to a shift in waste-based materiality in the discipline of architecture, mainly explored two types of recycled plastic (PET and TPU, which are easily accessible in daily use) with distinct qualities, resulting in a hybrid that changes from clear to opaque and from rigid to flexible. PET is commonly used in bottles and electrical wire coatings, and TPU is easily recycled from electronics casings, shoe soles, and so on. They have a similar density, which is 1.34–1.38 g/cm^3. However, TPU is softer, with a strength of only 45 MPa, while PET's strength is 150 MPa. Additionally, TPU also has a lower melting point, which is 220 °C, while PET melts at 267 °C.

In order to reuse waste-based materials, the research pays attention to the recycling method for plastic. In the UK, 7.7 billion bottles are used annually. The research aims to convert this waste into useful materials that can be used in building and architecture. Sorting and collection are the first steps in the plastic recycling process. Every kind of waste is collected and delivered to the appropriate location. The next stage in the research is to transform PET and TPU into flakes, which can then be used as 3D printing filament.

2.3. Testing the Properties of Plastic Materials

2.3.1. Fire Coating Test

The most common concern about using plastic in construction is what will happen in case of fire. However, plastic can be coated to prevent fire and its properties can be altered, just like any other material used in building. The fire experiment was conducted with PET and TPU sheets with a thickness of 3 mm and sample dimensions of 5 cm × 5 cm, subjected to burning with a candle flame with a temperature of 600 °C to 1000 °C in a closed indoor environment. Through tracking the combustion reaction over time in three replications of the burning experiment, it was observed that, without coating, PET caught fire after 30 s of being exposed to flame. The burning flame height was up to 5 cm and combustion speed was 0.1 g/s. After the plastic caught fire, smoke was released with a high density. After 40 s, the plastic started dripping, and the material eventually extinguished itself. Compared to PET, TPU caught fire more quickly, and took only 15 s. The highest burning flame height was 4 cm and the combustion speed was 0.06 g/s. Smoke was released with a lower density compared to PET and the material started dripping at the same time. After 30 s, the material began to self-extinguish. Figure 1 shows the PET and TPU burning tests without coatings.

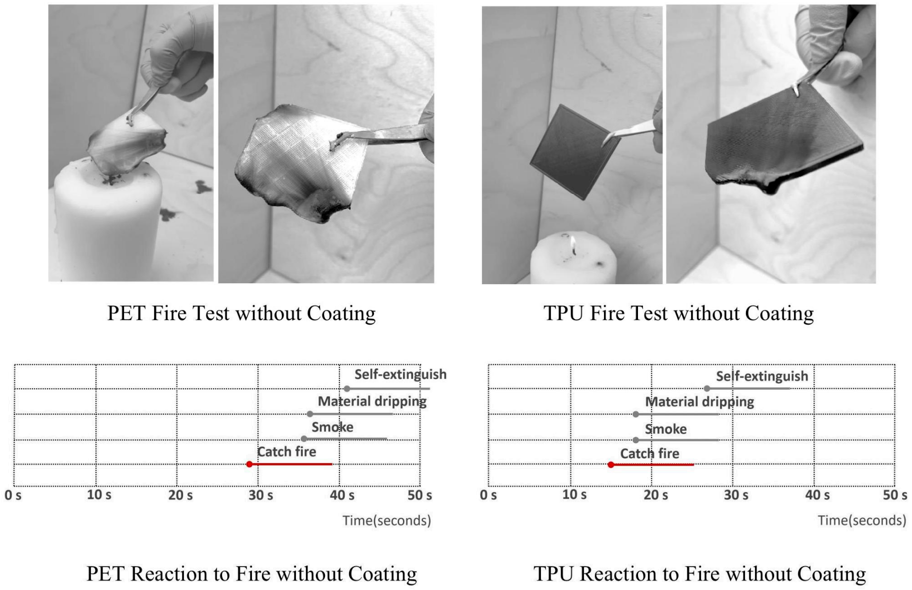

Figure 1. PET and TPU fire test without coating, catching fire quickly and self-extinguishing.

Then, the following experiment was conducted by coating the plastic sheets of 5 cm × 5 cm dimensions and 3 mm thickness with Brominated flame-retardant spray and subjecting them to burning in the candle flame with a temperature of 600 °C to 1000 °C in the same indoor environment. The Brominated flame-retardant spray is composed of polybrominated diphenyl ethers (PBDEs), tetrabromobisphenol A (TBBPA), other brominated compounds, solvents, and binders, sometimes also including fluoropolymers to improve water resistance. The application of these compounds can release bromine radicals during combustion, which stops flames from spreading. In addition, the flame-retardant spray is also applied as a thin film which is resistant to external conditions like moisture and UV exposure. It is generally durable for 5 to 15 years and can degrade over time due to environmental factors like UV radiation, temperature, moisture, and weather. Thus, reapplication is required every 3–5 years to ensure its effectiveness. From the combustion reaction over time, in three replications of the burning experiments, it was observed that PET did not catch fire when exposed to the same basic fireproof coating as TPU; instead, it converted to ash, which was the result of charring by flame after 30 s. Smoke was released with a high density after 40 s, and the sample quickly caught fire and extinguished itself. Similarly, after being exposed to flame for 15 s, TPU was charred and reduced to ash after 13 s, but did not catch fire. After emitting smoke with a much lower density compared to PET for 20 s, it instantly extinguished itself without catching fire. Figure 2 shows the PET and TPU burning tests with coatings.

From the fireproofing experiment, it is clear that coating can protect both PET and TPU from dropping and stop the flame from growing, but the coating choice, protection time, and effectiveness on plastic also need further research.

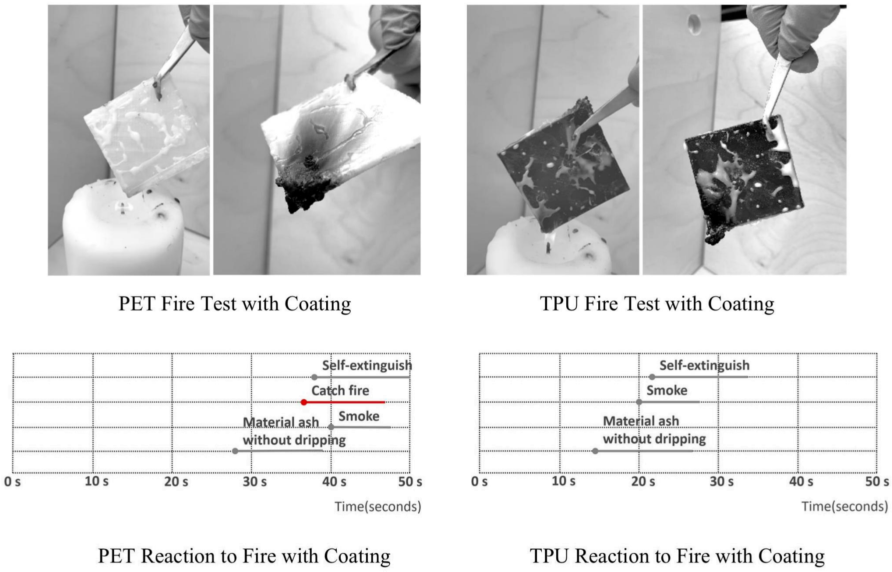

Figure 2. PET and TPU fire test with coating, not catching fire quickly and converting to ash.

2.3.2. Structure Strength Test

The structural characteristics of plastic are another point of contention. PET and TPU have different properties in terms of tensile and compression characteristics, such as rigidity and flexibility. PET's shore hardness is 95, and TPU's shore hardness is 70. A structure test was conducted with a compression machine by applying different strengths from 0 Mpa to 200 MPa at the mechanical engineering lab and documenting the results. PET is a hard material, so it broke under the compression of 80 MPa yield strength. However, TPU is a semi-rigid material with high resistance. It bent but did not break under compression. Figure 3 shows the PET and TPU structure tests when subject to compression.

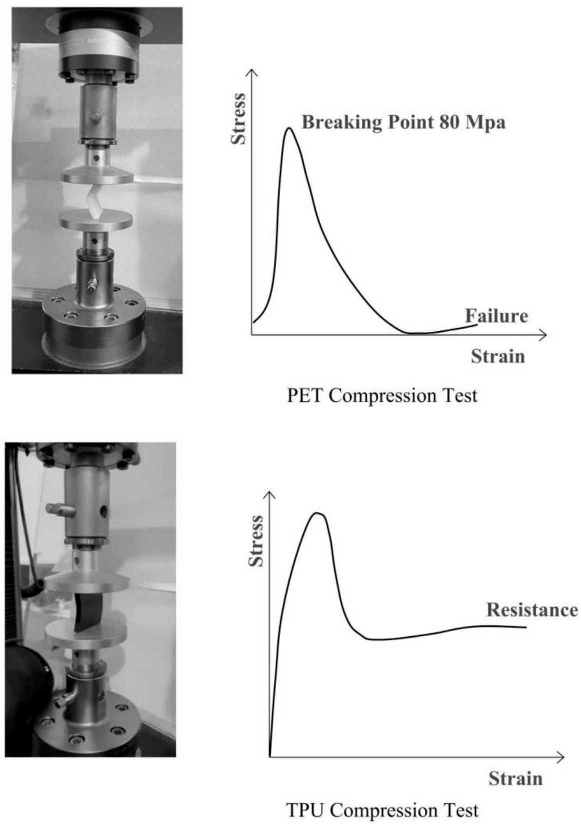

Figure 3. Hard PET and Semi-rigid TPU Compression Test.

2.4. Fused Experiment with Plastic Multi-Material

The work on the fused material started by combining two of the safest types of plastic, PET and HDPE, in the laboratory. Scissors were used to cut each bottle and pack so that the shreds would fit in the stainless-steel mold manufactured for the research. After that, the two kinds of material were mixed in the mold and heated in a kiln for half an hour at a temperature of 280 °C. The PET melted at 267 °C, while the HDPE melted at 210 °C. Another fused material experiment with pink HDPE and white PETE aimed to achieve a gradation of the two types and two colors using the same method of melting plastics at a temperature of 280 °C in a kiln. A chaotic pattern and two-color gradation were the outcomes of heating them together as shown in Figure 4. The area of 100% PET shows tensile strength of 70 MPa, while the strength of 100% HDPE is 37 MPa. The fused multilayer interface between 25% PET to 50% PET has a strength range from 10 MPa to 25 MPa, which indicates a low adhesion following the blending process after heating.

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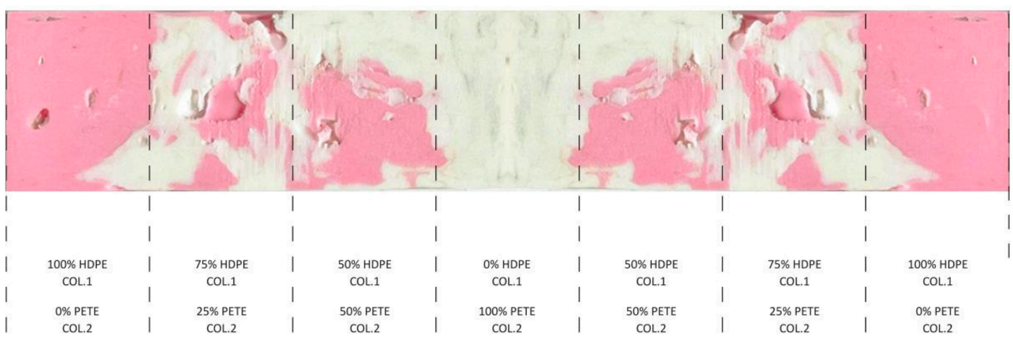


(**B**)

Figure 4. (**A**) Pattern gradation after mixing different-colored PET and HDPE in a stainless-steel mold and heating at a temperature of 280 °C in a kiln for half an hour. (**B**) Pattern gradation after mixing pink HDPE and white PET and heating at a temperature of 280 °C in a kiln.

2.5. 3D Printing Experiment with Dual-Color Multi-Material

The multi-material gradation and pattern created by heating and fusing various materials in a kiln is chaotic and stochastic. However, there are situations where controllable and rational gradation is required in production, and this can be achieved through 3D printing technology with a dual-extruder machine. The following experiment aimed to create a multi-material with manageable color gradation towards intended direction via 3D printing by using a dual-extruder printer. Black and white PLA or blue and white PLA were used to achieve multiple directions of gradation. The color mixing settings were achieved in the Geeetech color mixer by setting different filament percentages for each nozzle. Figure 5 shows the 3D printing results of different color gradations.

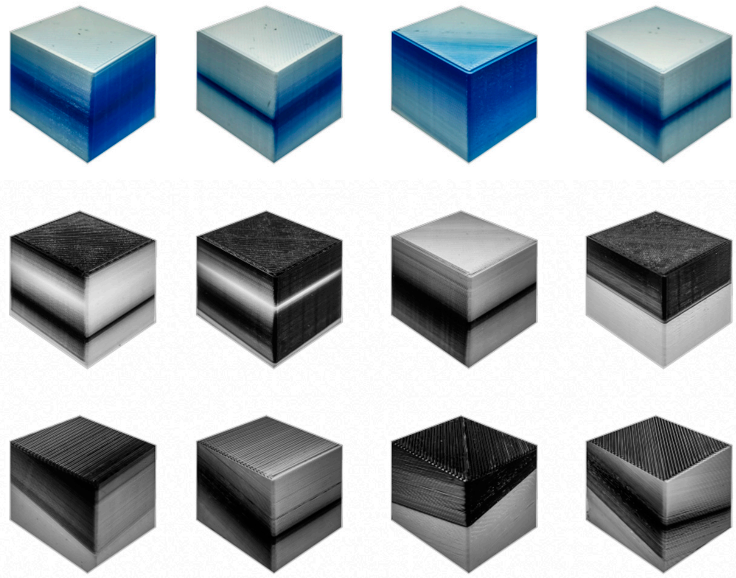
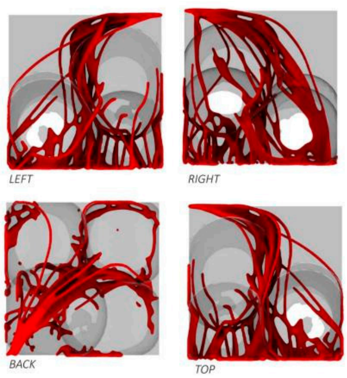
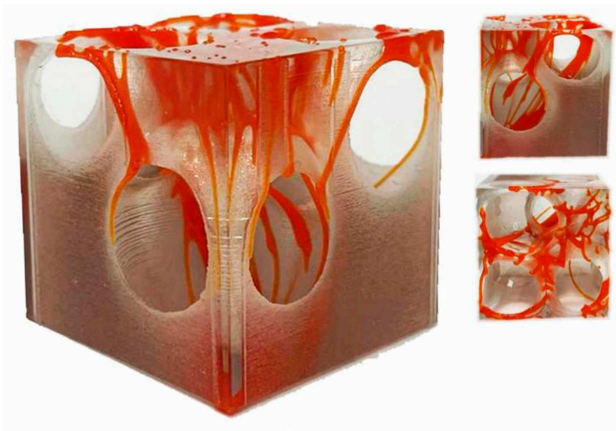


Figure 5. Three-dimensional printing of manageable gradations in intended directions with different colors of PLA filament.

Then, using a Stratasys 3D printer, two colors of resin (red and transparent) were used to print the sphere and cube Boolean subtraction model. In the Stratasys 3D printer, pre-colored resins are utilized to create distinct color areas, achieving full-color 3D printing. Different-colored resins can be blended and color combinations can be created directly in the printer without post-processing. During the printing process, the Orient tool in the GrabCAD Print (version 1.50 released in January 2021) can be used to adjust print orientation, which aims to align the flat surface of the model with the build platform. The optimal print orientation significantly affects the surface finish, printing accuracy, and build time. Figure 6 shows the multi-colored resin enclosure conveyed with different aesthetics and porosity.



Facades of Digital Model for Stratasys 3D Printing



Stratasys 3D Printing Model with Red and Transparent Resin

Figure 6. Facades of digital model for Stratasys 3D printing and Stratasys 3D Printing Model with Red and Transparent Resin.

3. Fused-Space Design Methodology

3.1. Design Concept

Engagement with materials can change how humans act and think [23]. This has stimulated new design styles inspired by nature, like biology building and organic building [28], which are the result of paying attention to natural intelligence with the help of multi-material, thus stimulating the appearance of new aesthetic criteria for building. The fused-space design methodology is inspired by natural textures like the continuous holes or random patterns in organic materials. Based on this, this research explored possible algorithms that could be used to achieve these kinds of organic structure and texture gradation in building design.

3.2. Digital Design Algorithms

The detailed design process started with the sphere packing algorithm [15] with a complete bounding box as the original environment, and applied a Boolean methodology to obtain the in-between space of the space enclosure. The next step was to fill the in-between space using digital algorithms such as Swarm Behavior [16], Game of Life [17], Voronoi [18], and Shortest Path [19]. The following step was to apply material gradations like thickness, density, transparency, and flexibility based on structure analysis, daylight analysis, and privacy analysis to obtain different space qualities. Finally, the prototype design was achieved with material gradation and model voxel for fabrication. Figure 7 illustrates the whole design process.

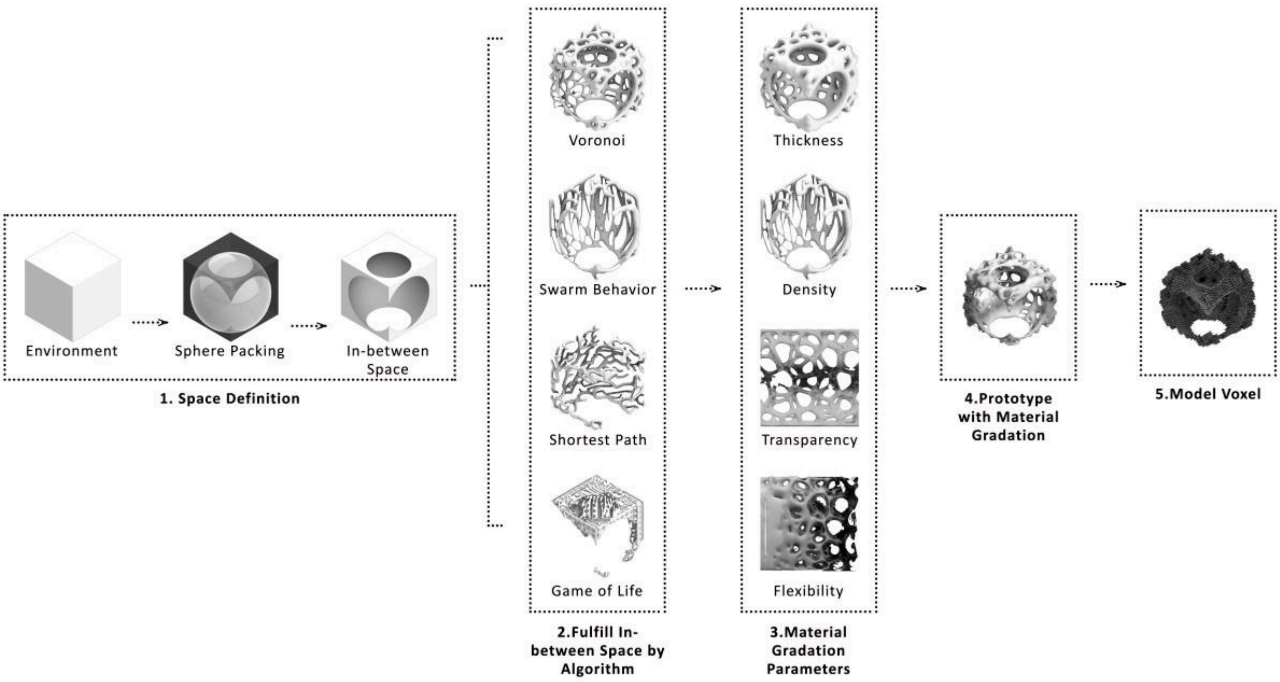
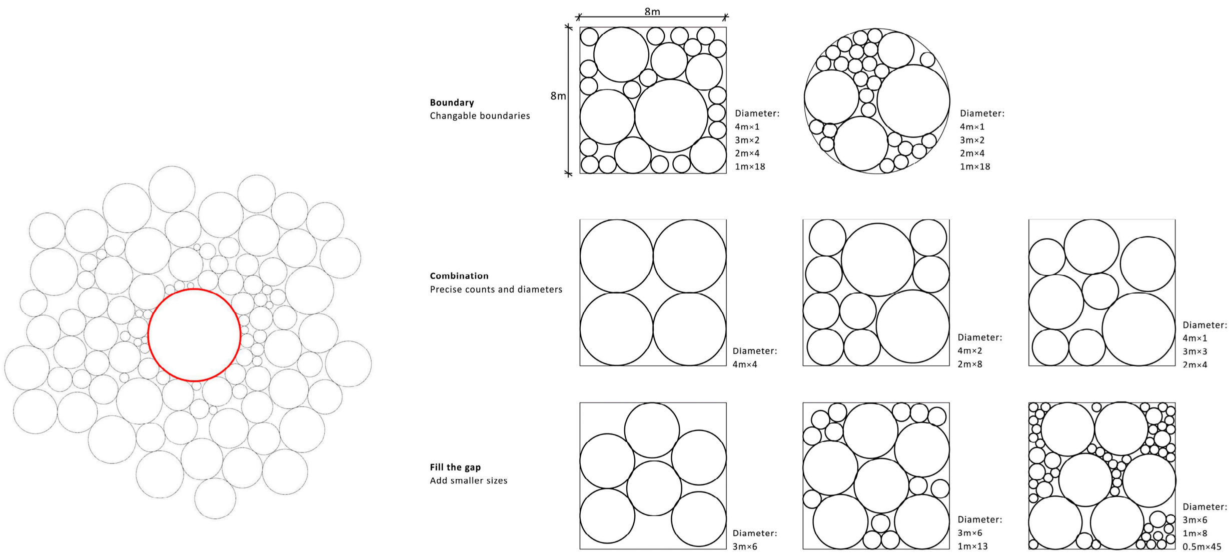


Figure 7. Digital Design Process from Space Definition to Voxel Model.

3.2.1. Space Definition Through Circle Packing and Sphere Packing Algorithms

The design process began with using the circle packing and sphere packing computation, an algorithm that can automatically generate a large number of space options to define and create flexible spaces. As shown in Figure 8A, the circle packing algorithm helps to define the plan of space, which can create different boundaries, space combination methods with different circle radii, and the number of circles to fill the gap in the boundary. Figure 8B displays the sphere packing algorithm, which aims to define the sphere volume to create different sizes of space, which are controlled by sphere number, collision, and gravity.

The gravity parameter can prompt the sphere to drop down toward the ground plane and help it to have sufficient area on the ground level, ensuring the spaces' base alignment. Through controlling the collision parameter, the interface between spheres' intersections can be squeezed into a stable and flat floor, which results in the sphere spaces' stability. To define and create various space choices, the site can be packed with spheres of different counts and volume, and then spheres interact with the boundary, gravity, and each other.



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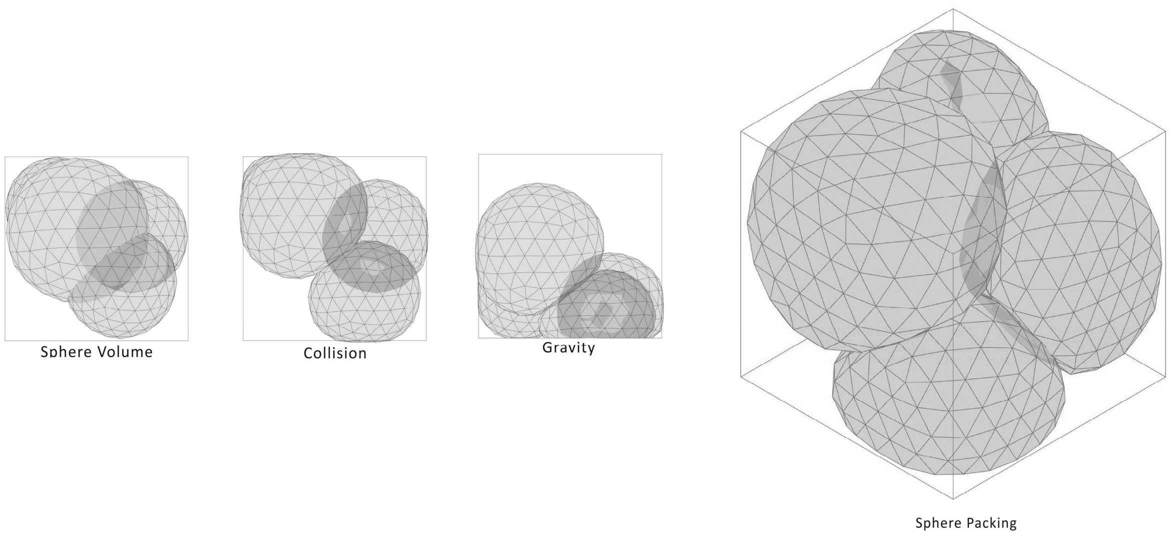


(**B**)

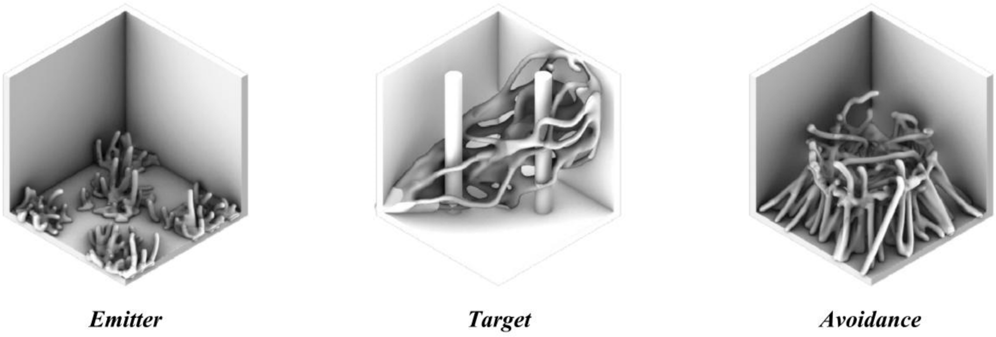
Figure 8. (**A**) Circle packing methodology with various boundaries, radii, and numbers of circles. (**B**) Sphere packing methodology controlled by sphere number, collision, and gravity.

3.2.2. Filling in In-Between Spaces Through Forming Algorithms

Once the space has been specified by sphere packing, the geometry of the in-between space, also known as the space enclosure, is the next thing to consider. In order to create the carved mass of enclosure, a variety of nature-inspired forming algorithms were employed such as Swarm Behavior [16], Game of Life [17], Voronoi [18], and Shortest Path [19]. Using this approach, morphological computation may give the appearance of life to a lifeless substance, such as plastic, because design is no longer a slave to form.

Swarm Behavior

The first algorithm is Swarm Behavior, which is based on the swarm intelligence extracted from the social behaviors and social interactions in bird swarms, perhaps milling about in the same spot or perhaps moving en masse or migrating in some direction [16]. There are three main forces to simulate this behavior, which are Alignment, Cohesion, and Separation. Figure 9A displays the essential control elements of Emit, Target, and Avoidance which define the swarm behavior route. Emit and Target can be defined as the start point and end point in spatial cubes, and control the width and length of whole space area. The Avoidance zone can be described as a cube, sphere, or other geometries which the behavior movement cannot reach, determining the inner functional space and translating the generated swarm behavior pattern into the space enclosure. In the real-world space generation process, the gravity of the Avoidance zone should be taken into consideration, ensuring the inner functional space room is ground-based. Some carved space enclosure results created by Swarm Behavior computation are illustrated in Figure 9B. Swarm Behavior is preferable in the design of spaces with variable openness requirements, because the swarm route is defined by the Emitter and Target, which makes it convenient to control the closed enclosure area and reserve the open area.



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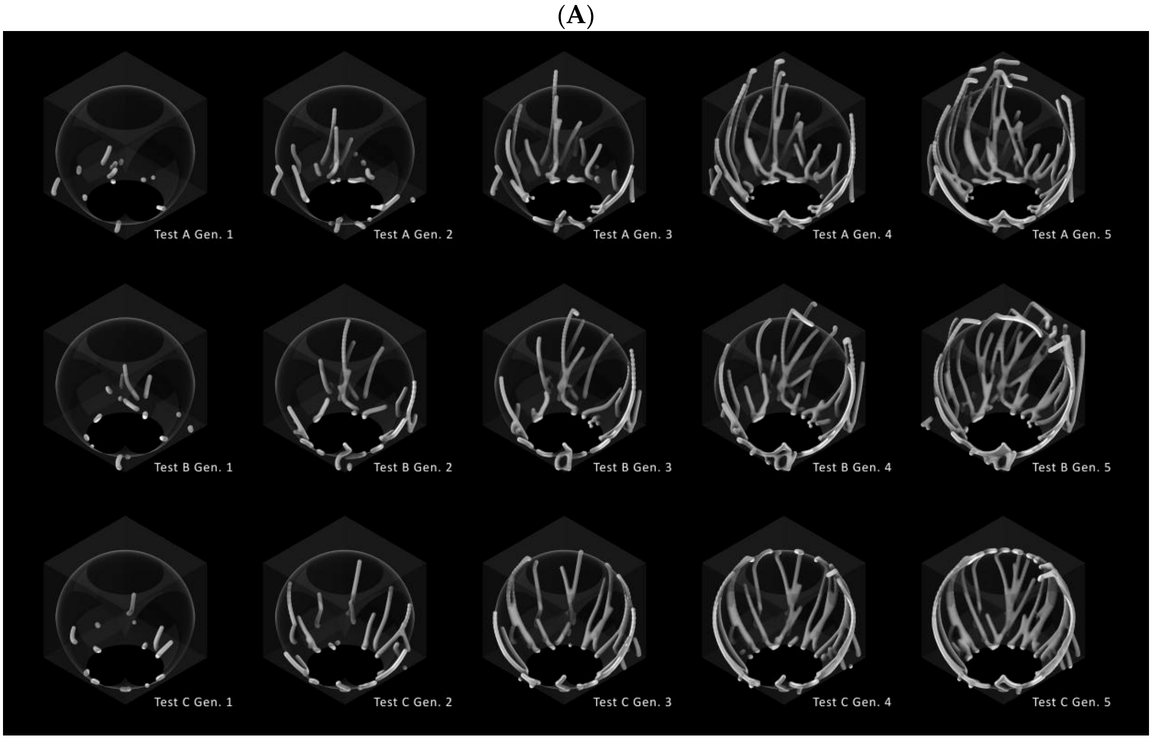


(**B**)

Figure 9. (**A**) Emitter, Target, and Avoidance controlling elements for defining the Swarm Behavior route. (**B**) Computation results of Swarm Behavior algorithm with different forces and rules.

Game of Life

The next algorithm is the Game of Life. The British mathematician John Horton Conway created a cellular automaton known as Conway's Game of Life in 1970. Since it is a zero-player game, no additional input is needed; instead, the game's evolution is dictated by its starting state. One interacts with the Game of Life by creating an initial configuration and observing how it evolves [17]. There are four main rules that control the Game of Life computation. Rule A: Any live cell with fewer than two live neighbors dies, as if by underpopulation; Rule B: Any live cell with two or three live neighbors lives on to the next generation; Rule C: Any live cell with more than three live neighbors dies, as if by overpopulation; Rule D: Any dead cell with exactly three live neighbors becomes a live cell, as if by reproduction. Since this algorithm is stochastic and complicated during the generation process, in order to ensure space consistency and repeatability in the fabrication process, multiple simulations were generated and averaged with each kind of fixed seed and rule. Figure 10 shows some testing results of Game of Life with different rules and various numbers of seeds. Because of the stochastic property of Game of Life, it is more suitable for creating flowing and flexible "maze" spaces with complicated function and program requirements.

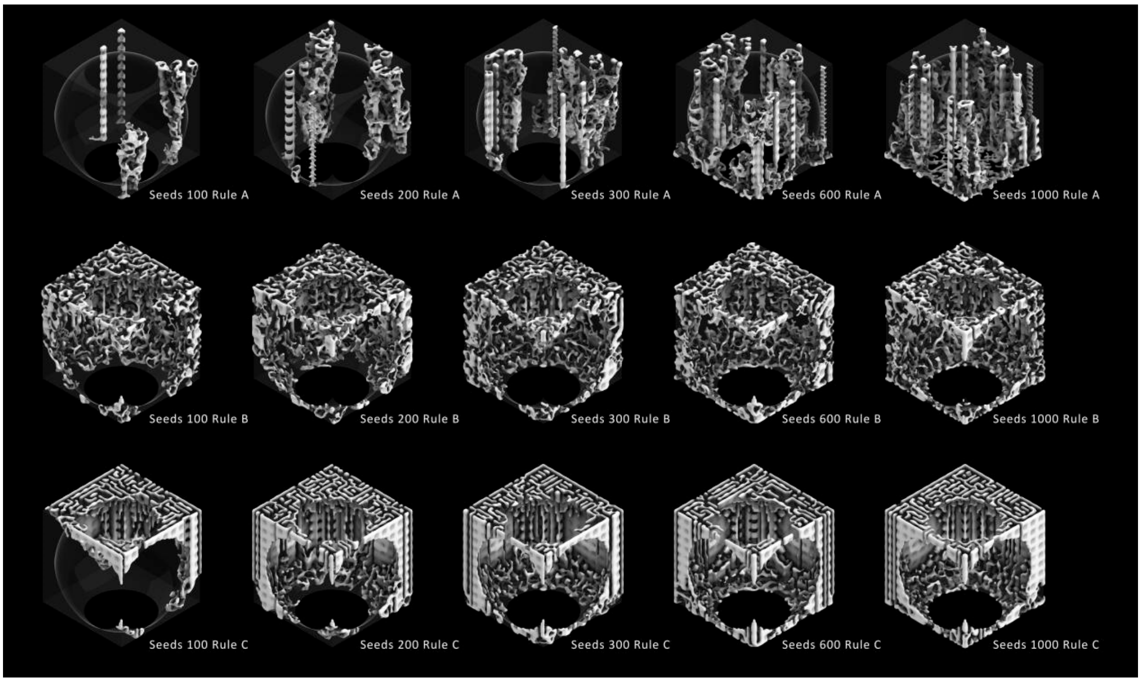


Figure 10. Game of Life algorithm with different rules and various numbers of seeds.

Voronoi

The third algorithm is Voronoi, which is composed of half lines and segments that make up each center's Voronoi area borders. For any center, the set of points on the plain that are closest to that center is known as the Voronoi area. A Voronoi diagram is defined for a given set of N points as a plain divided into N areas in such a manner that each point in any cell is closer to a specific point from a set of n points than the remaining N − 1 points. The Voronoi cells produce convex polygons in two dimensions and convex polyhedral shapes in three dimensions [18]. In Grasshopper, the constrained boundary conditions in Voronoi can be achieved by giving a bounding geometry like a surface or Brep, which stops the circle growing to infinity. In addition, in order to avoid excessive porosity, the minimum distances between cells can be controlled with the Voronoi component in Grasshopper by inputting points of adjustable number which can be generated randomly using the

Populate Geometry component, and giving a controllable number to the radius for circle growth. Thus, it is easy to control different densities and porosity by giving different points and rule settings. Furthermore, Voronoi's mechanical properties are highly influenced by their unique patterns, enabling notable behavior in high strength-to-weight ratio, tunable stiffness, and improved stress distribution, which is preferable in spaces with lightweight structure and gradation structure requirements. Voronoi computation was used to produce several carved space enclosure outcomes, illustrated in Figure 11.

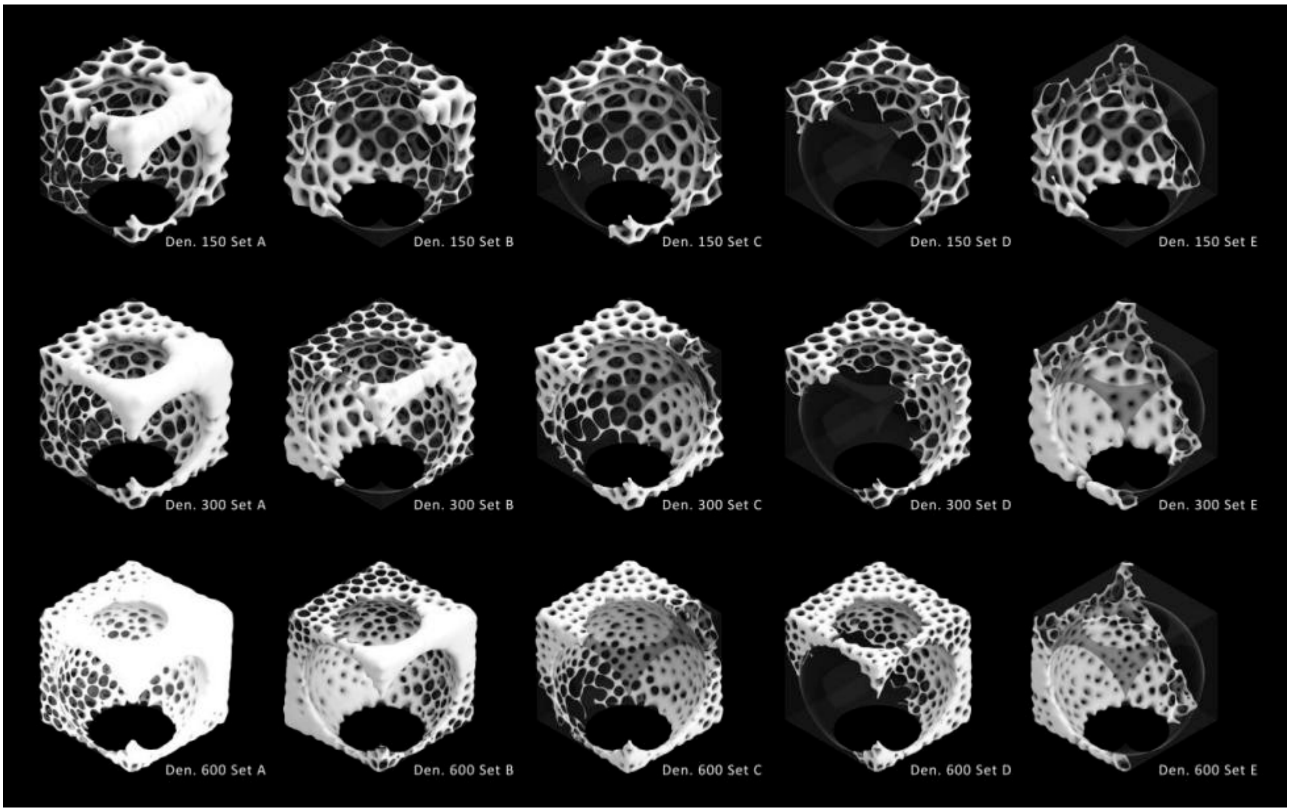


Figure 11. Voronoi algorithm with different densities achieved by giving different points and rule settings.

Shortest Path

The last algorithm is Shortest Path, which aims to find the most efficient path involving the minimal cost between two points in a graph or network. Usually, a source node and a group of other nodes are involved, and the algorithm keeps track of the distances between the source and each other node [19]. Shortest Path uses weighting factors like distance, cost, and time while traversing a specific edge in a geometry, aiming to find the optimal path between nodes, determining the overall path length and the density of the generated shape. Mathematically, it can be represented as finding a path (P*) between a source node (r) and a target note (v), then minimizing the length: Length (P*) = min {length (Prv) | (Prv) is a path from r to v} [29]. The tracks connected by the source node and dispersive nodes easily form a radiated enclosure shape, which can be adopted under the condition of a higher insolation requirement towards a specific daylight direction. It can be controlled by giving different counts of nodes and track rules, resulting in different densities and porosities of enclosure, as shown in Figure 12.

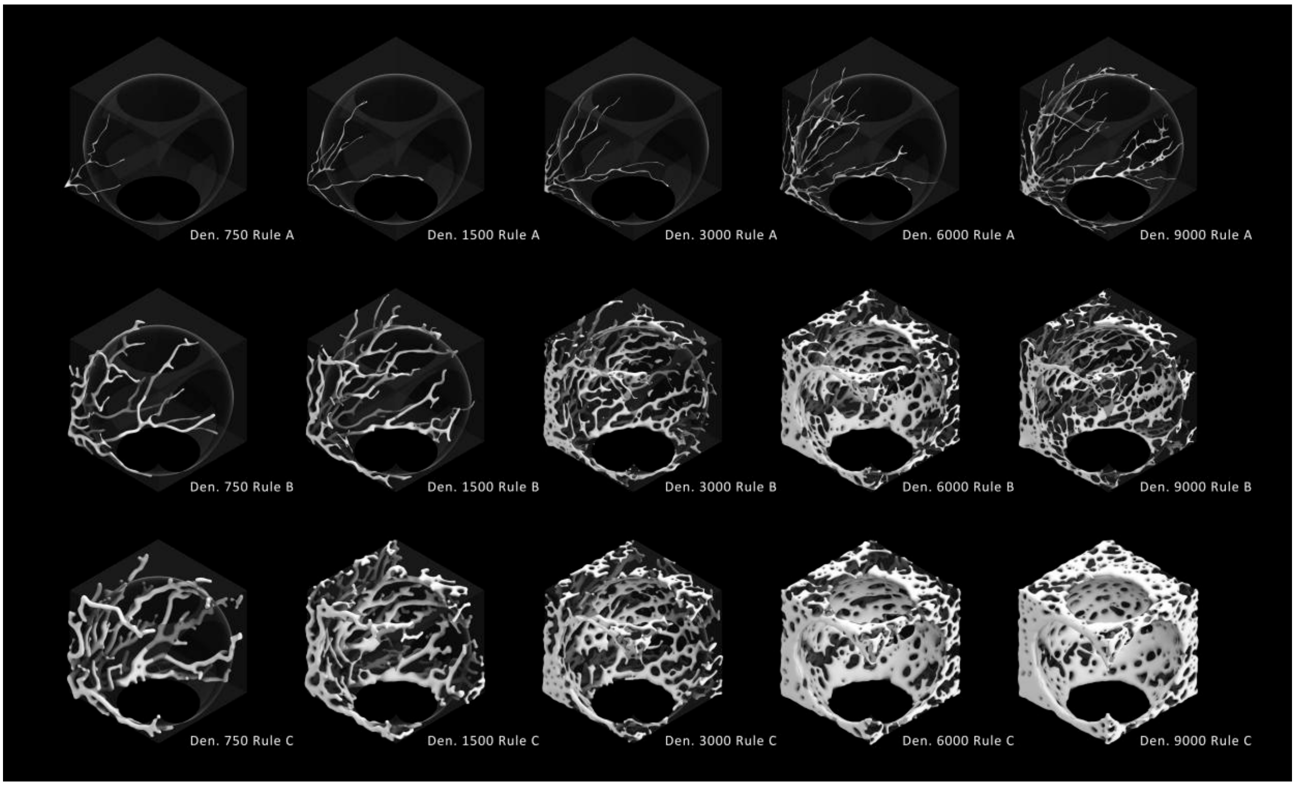


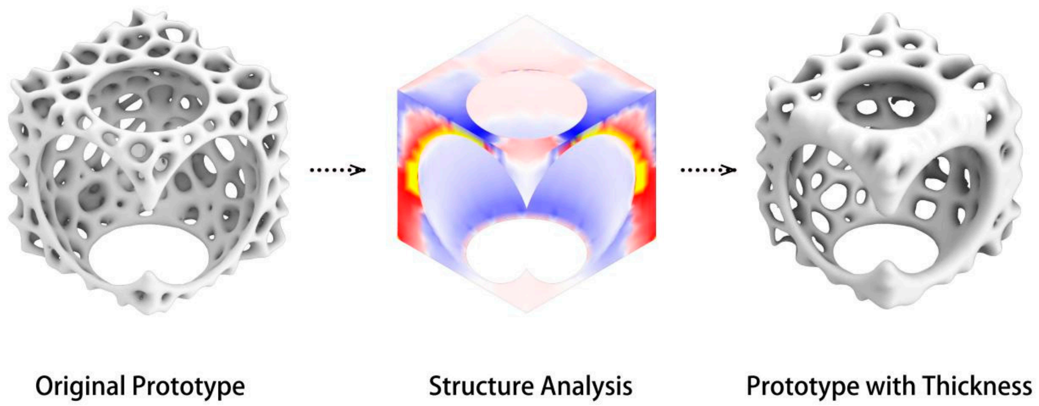
Figure 12. Shortest Path algorithm with different densities achieved by giving different counts of nodes and track rules.

3.2.3. Space Properties Affected by Multi-Material Gradation Parameters

Following generation of the space enclosure, different gradation parameters, like thickness, density, transparency, and flexibility, were also applied to the prototype design, which was intended to create a variety of space properties. The gradation parameters were based on the research into daylight analysis, structure analysis, porosity analysis, and openness analysis.

Thickness Graduation with Structure Analysis

Based on the normal algorithm prototype, material was distributed with different thicknesses and changed the basic prototype. The thickness gradation was based on the structure analysis. This research analyzed the prototype's structure using the Karamba plug-in in Grasshopper, which allows for insertion loads or support parameters. Through inputting the gravity load, which acts on the whole structure, and the specific point load, setting plan supports, and plastic material constraints, the analyzed model was visualized via color mapping, representing the model's response under the external loads and guiding utilization of the material. The resulting diagram with the color gradation can be translated into areas with more or less thickness. The color gradation can then be applied to fundamental algorithms such as Voronoi, Swarm Behavior, Shortest Path, and Game of Life. The prototype will then have varying thicknesses according to the various color gradations, as illustrated in Figure 13A. The thickness can be distributed across different areas and achieved with various radii of structure. Where there is more load, there will be higher thickness and density. When creating a fused space, thickness gradation can be used to determine the distribution of materials and the strength of the structure. Testing results for the Voronoi, Swarm Behavior, Shortest Path, and Game of Life digital algorithms with varying strengths based on the color gradation of structure analysis are displayed in Figure 13B. Their performances are distinctive and comparative in the multiple algorithms' patterns, loading positions, and path radii, which are adaptive to different strength requirements.



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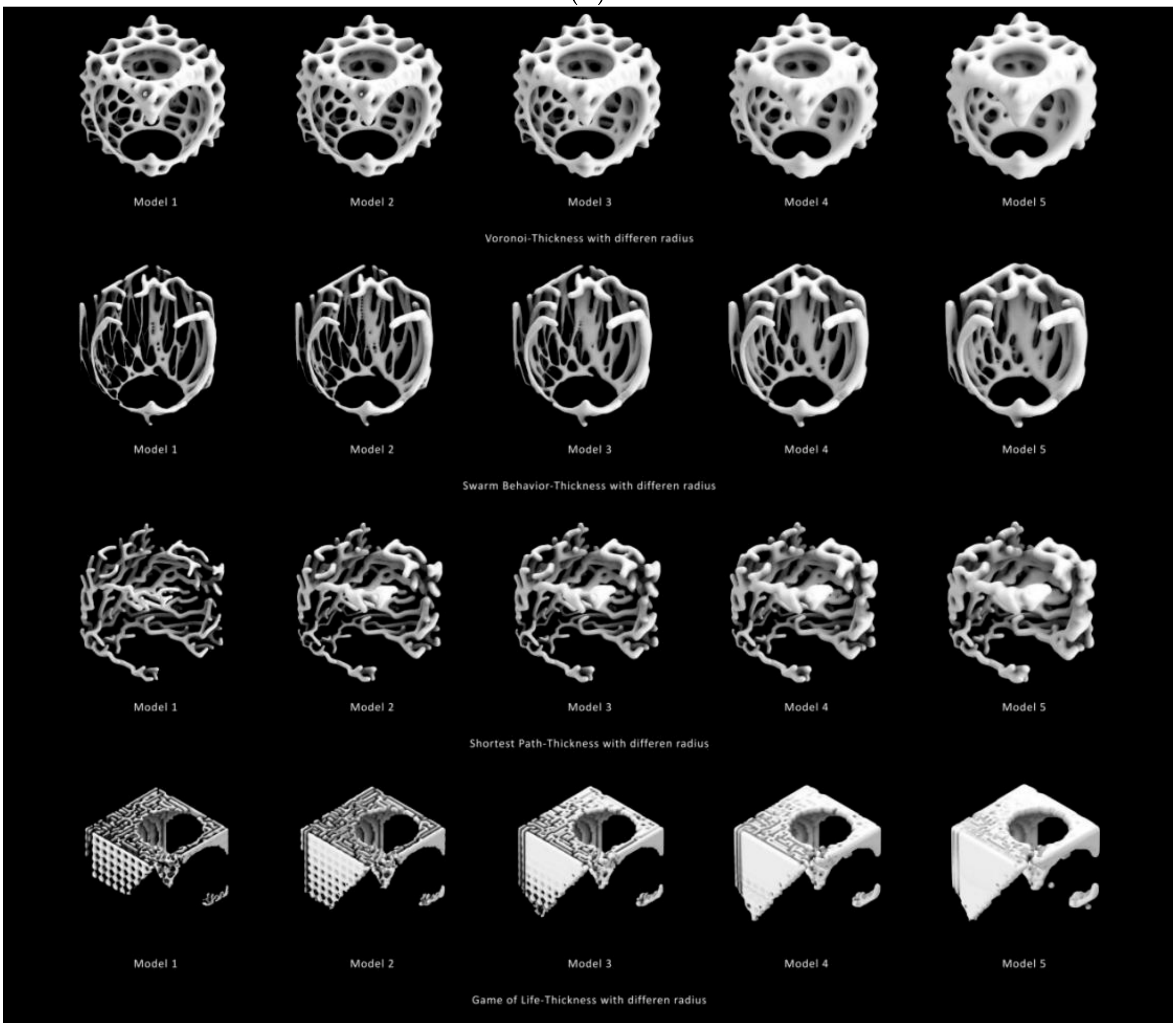


(**B**)

Figure 13. (**A**) Thickness gradation based on color mapping diagram from Karamba structure analysis. (**B**) Digital algorithms with different strengths based on color mapping diagram from Karamba structure analysis.

Density Gradation with Privacy Requirement

Through fixing emitter counts and computing space in the algorithm, a space enclosure with a series of variable densities can be achieved. The density and radii of the pattern depend on the need for space privacy. A space enclosure created by algorithms like

Voronoi or Swarm Behavior with 3D printing can have a lower density where the area should be more exposed to the outside. On the other hand, a more private area can be enclosed by a high-density space enclosure. A new space's enclosure density is arranged according to a different design and the number of holes or their radii. As Figure 14 displays, Voronoi digital algorithms were used in density gradation experiments, producing varying porosities and visibilities from 16% to 77%.

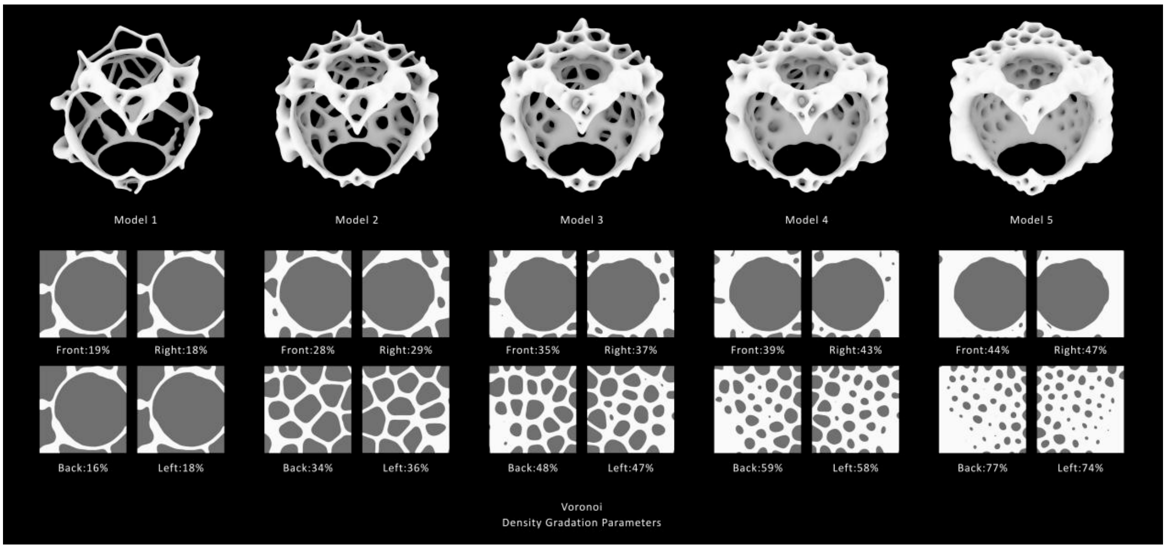


Figure 14. Density Gradation from 16% to 77% of Voronoi Algorithm.

The density of enclosure, which is determined by the pattern's porosity, radius, and number of holes, determines the wall's visibility and the privacy of the area. The visibility was validated through conducting analysis of the viewability rate by comparing the openness area and the whole wall area at the height of a human's eyes. The porosity of the pattern shown in Figure 15 can affect the viewability rate of the enclosure by 95% to 5%, while the radius and density of the circle also change the viewability rate by 90% to 25% and 10% to 50%. Depending on the user's requirements for privacy and space visibility, the pattern can be employed in the construction of fused spaces with specific requirements.

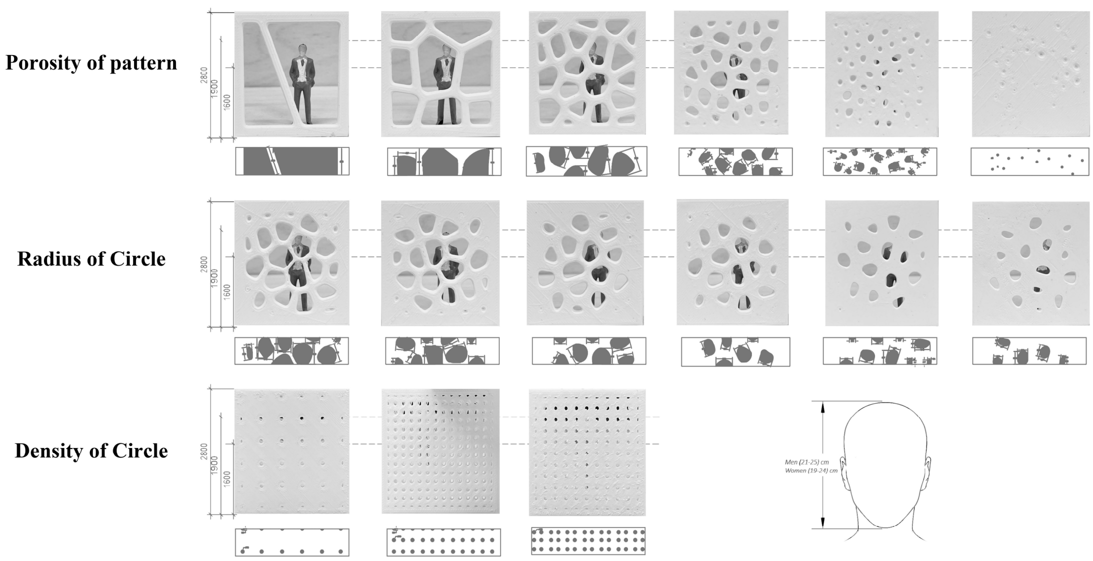
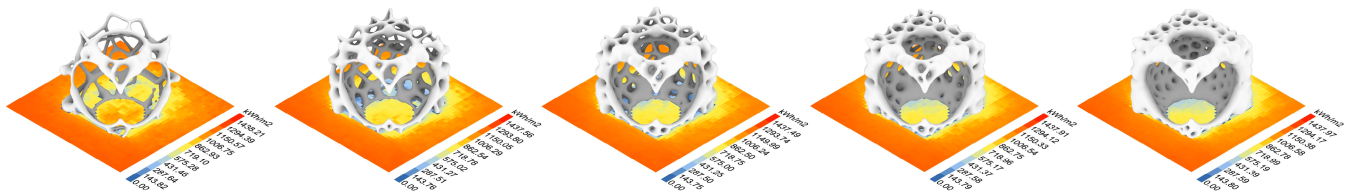


Figure 15. Wall's privacy and visibility determined by the density of enclosure transparency gradation with incident radiation (daylight analysis).

Transparency Gradation with Daylight Analysis

Transparency gradation is connected to daylight analysis. Where there is more daylight on the target place, the fused space is intended to use material which is more transparent to ensure the place receives enough daylight. With this goal, the researchers performed daylight analysis through a digital algorithm. The digital algorithm used in transparent gradation is based on incident radiation on the specific site. Using the Ladybug plug-in in Grasshopper, digital analysis was performed to obtain the site's daylight parameter diagram, and Figure 16A illustrates the incident radiation (daylight) parameter applied to Voronoi enclosures with different densities. The generated color mapping diagram shows the incident radiation of each area, from 0 kWh/m^2, marked with blue color, to 1435 kWh/m^2, marked with orange color. The color gradation from blue to orange in the mapping diagram can be translated into multi-material property gradation from opaque to transparent, which can be seen in Figure 16B. Where there is deep orange in the color mapping diagram, which means higher incident radiation on the target place, the space's corresponding material property is more transparent, ensuring the area receives enough daylight and producing a lighter atmosphere in the space.



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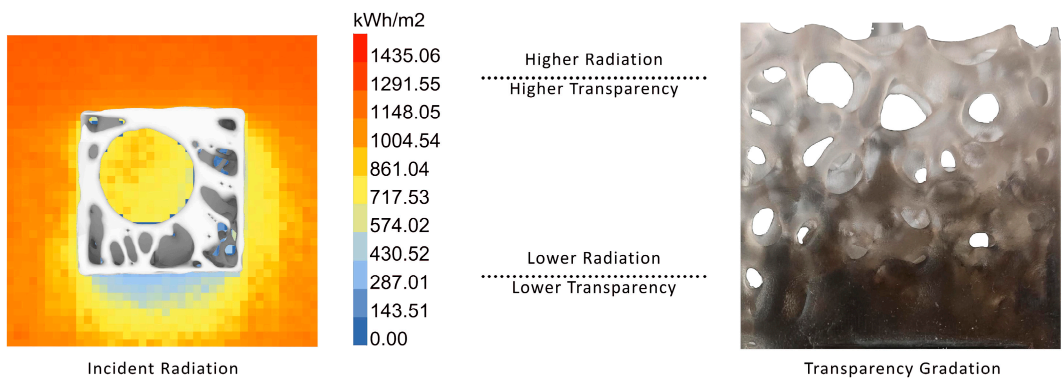


(**B**)

Figure 16. (**A**) Incident radiation (daylight analysis) with Voronoi enclosures of different densities. (**B**) Transparency gradation based on incident radiation (daylight analysis). Higher radiation is related to higher transparency.

Thus, based on the incident radiation gradation diagram, the required material transparency gradation can be obtained in the structure of the prototype. To attain transparency gradation in a fused space, specialized multi-material techniques can be applied. For this design, transparent PET and opaque TPU were chosen; by blending the two plastics, the prototype design would be able to produce a gradation between the transparent and opaque materials.

Furthermore, using multiple sheets of material can also affect transparency gradation. It is simpler to investigate the activity taking place in the inner room when the material is sufficiently clear. The transparency of the material and the visibility of the area behind the material gradually change when the transparent plastic sheets are stacked. Figure 17 displays the test results of the progressive change in transparency when one to six layers of transparent PET sheets were stacked, which established different levels of visibility of the space behind the material. Therefore, transparency gradation in a fused space can also be achieved by stacking multiple layers of transparent material.

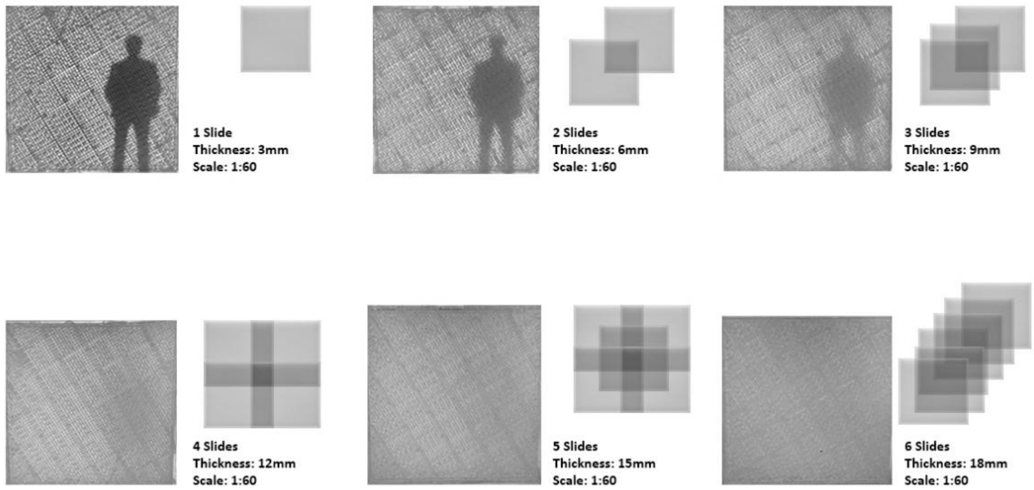


Figure 17. Progressive gradation in transparency achieved by stacking multiple layers of PET sheets.

Flexibility Gradation with Openness Requirement

Flexibility gradation is used to create a flexible entrance or window in a fused space by using the soft TPU material and hard PET material. The gradation from hard to flexible in the multi-material enclosure is translated from the privacy and openness requirements for the space. Through function and utilization analysis of the space's room, the amount and positions of windows and doors in the space's facade can be defined, which is the mapping methodology used to confirm the area of flexibility transition. The flexibility gradation implemented in these entrance areas can achieve an open section and the transition of the quality of the space from private to public. Then, material gradation is created in Grasshopper by merging the parameters of the two kinds of materials according to study of the openness of the space. The flexible portion can serve as an interaction medium between two areas when it is embedded into the entire hard substance. It can be opened like a window or door to facilitate communication and provide a path to exit. The cyclic loading in the flexible portions of these windows and entrance areas can be tested by applying and removing a compression load of 200 MPa repeatedly, using a compression machine at the mechanical engineering lab. As TPU is semi-rigid with insufficient strength, the test results recommend that, in order to enhance its durability and resistance to failure under fluctuating stresses, additional support like a metal core is necessary in real-world space construction. The proportion of flexible material depends on how open the designed area is. More flexibility means less seclusion and an area that is more exposed to the outer world. The shift from a public to a private area is signified by the transition between soft and hard materials. The combined flexible TPU and hard PET will be utilized in the construction process of the fused space to create a multi-material enclosure as shown in Figure 18, which will be based on the requirement of space openness.

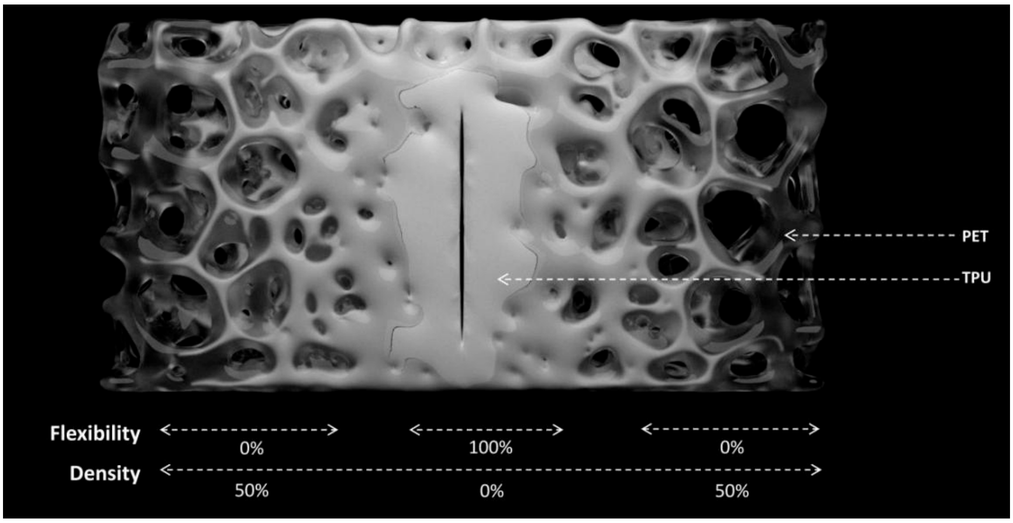


Figure 18. Flexibility gradation with PET and TPU material based on space openness requirements.

Overall, Figure 19 displays the final prototype of a fused-space enclosure generated by digital algorithm with several material gradation parameters, including the thickness gradation, density gradation, and transparency and flexibility gradation. The spatial performance of the enclosure can be validated by analyzing structure strength by Karamba analysis, incident radiation by Ladybug plug-in analysis, and viewability by porosity analysis. Through analysis, the structure strength is observed to vary from 200 MPa to more than 1000 MPa based on distinctive thickness gradation, while incident radiation changes from 0 kWh/m^2 to 1004 Wh/m^2 based on transparency and density gradation, and the viewability rate shows a range of 0% to 75% according to porosity gradation. Adaptive and adjustable gradation increase the structurally and environmentally viable properties of the visual enclosure.

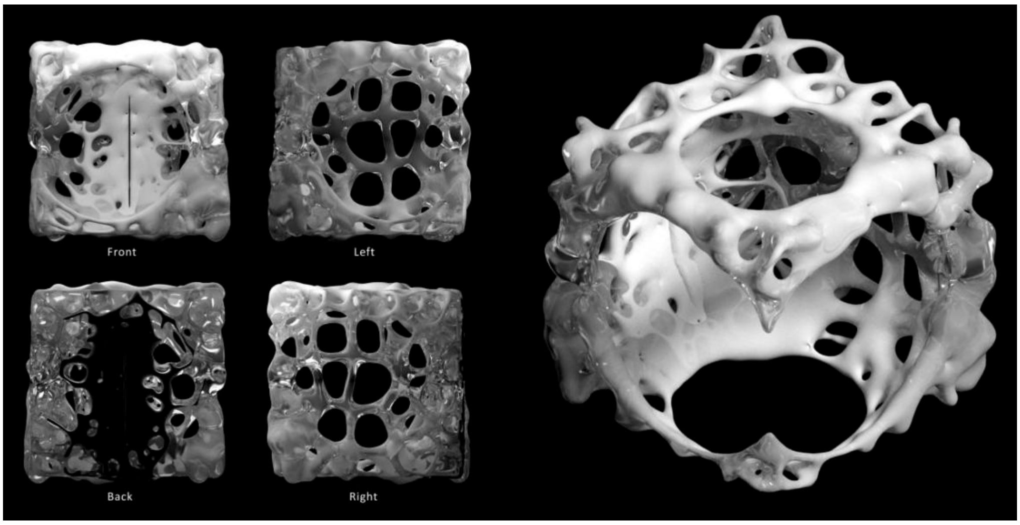


Figure 19. Prototype Design with Various Material Gradation Parameters.

4. Robotic Fabrication and 3D Printing Experiments

4.1. Toolpath in Voxel

This research experimented with robotic fabrication and 3D printing using plastic filament in the lab, adhering to the above-mentioned fused-space design methodology, which implemented sphere packing computation and digital algorithms like Swarm Behavior [16], Game of Life [17], Voronoi [18], and Shortest Path [19] to form the complex prototype model with various multi-material gradations for robot fabrication. In general, additive manufacturing includes three-axis printing, which requires significant investment of time, resources, and labor. To boost efficiency, this research used a six-axis robot in the experiment to create the model voxelization. Figure 20 displays the detailed toolpath of the voxel with the six-axis robot; in each diagram, the printing path of every step is indicated by the red line.

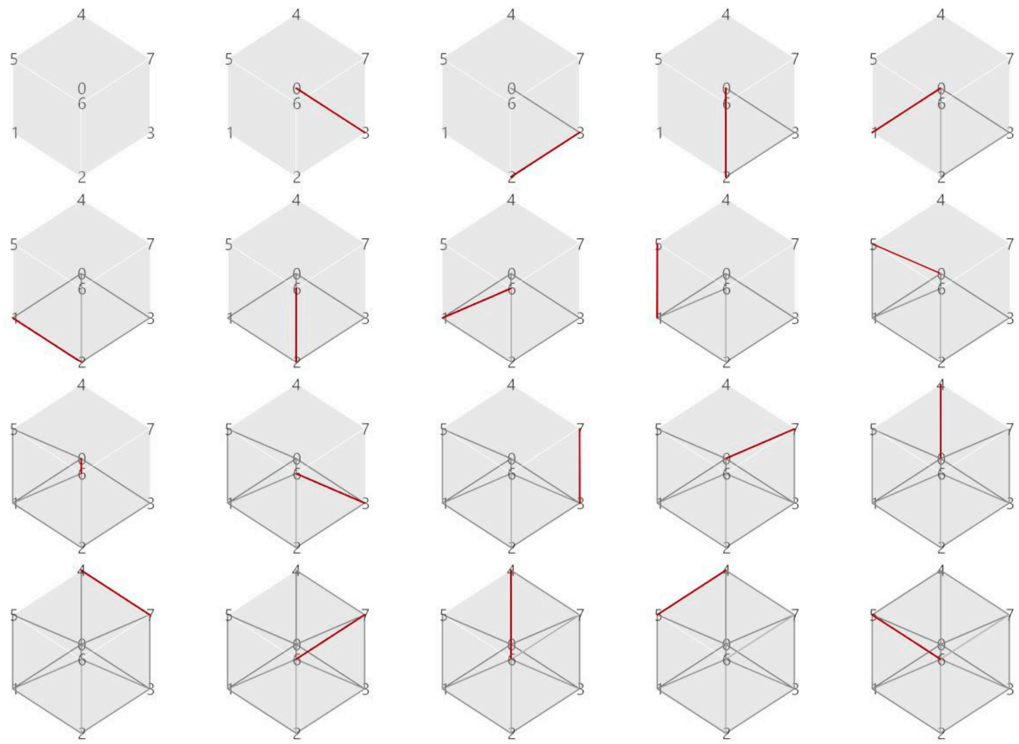


Figure 20. Toolpath of voxel with six-axis robot for 3D printing. The red line indicates the printing path of every step.

Based on six-axis printing, in order to print with a robot while keeping the intended complex form designed, the research converts the robot toolpath to voxel, achieving translation from a design model to a lattice structure for printing. Voxel toolpathing can convert the design's complex 3D geometry with multiple gradations and complicated pattern into a voxel-based structure composed of a collection of small lines and cubes. The voxel data makes it easier to generate toolpaths, ensuring precise movements of the robots and simulating efficient and accurate material removal and deposition.

4.2. Improvement of Robotic Fabrication Machine with Dual Extruder

The Dual Force V1 (3D Printing Machine with Dual Extruder)

Additionally, the researchers upgraded the lab's robotic arm so that it could print using two filaments instead of just one. Dual or multi-extruder printing heads are often used in material extrusion systems to print multiple multi-material parts at once [30]. Dual force is the lab's first dual extruder attached to a robotic arm. The researchers designed and built a new extruder, aiming to print two types of material that require different speeds and temperatures to achieve a gradation from material A to material B. Compared to single-extruder systems, the upgrade of the robotic arm with dual-extruder printing enabled printing with multiple colors and materials in a single print, creating more complex and appealing objects with greater efficiency and enhancing the functionality of the printed object by combining materials with varying properties in specific areas.

Initial testing was conducted on two colors of PLA, designated as materials A and B. The extruder is made up of a main board, two blowers, two Titan extruders (one for material A and one for material B), a motor, a two-in-one-out dual-color metal extruder with a specially made brass hot-end, and a holder. The main parts can be seen in Figure 21. Furthermore, a new electrical box had to be made to meet the dual motors' needs. An Arduino Duo motherboard controlled all the parts, including a switch for digital output, two stepper motors, two stepper motor drivers, a heat block, and a temperature controller.

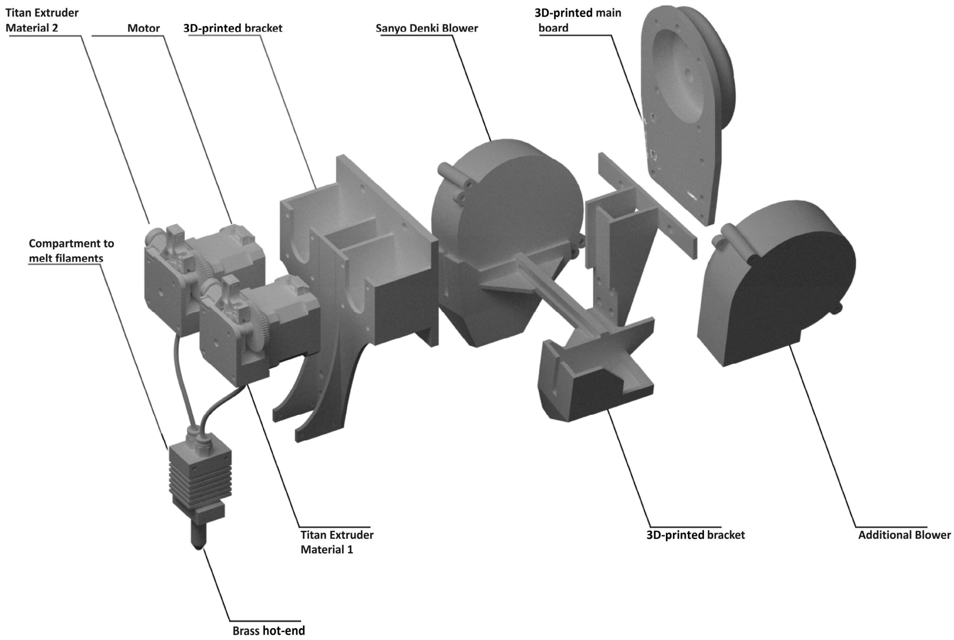


Figure 21. The Main Components of the Dual Force V1.

Each component's primary function is outlined below:

Main Board—3D printed with semi-flexible material to avoid breaking during the robotic arm's movement.

Additional Blower—To speed up cooling of the plastic after melting. Working with PET and TPU at the same time, it is necessary to decrease the cooling time, because they have different melting and cooling temperatures.

Titan Extruder 1 and 2—Performance, power, and push. A Titan extruder brings high-performance, lightweight extrusion.

Motor—The compact but powerful motor is used for driving gears or directing extruders.

Dual extruder with hot-end—Two-in-one-out dual-color metal hot-end extruder kits with the cable 0.4 mm brass nozzle.

Furthermore, in the printing process of the dual-extruder setup, proper calibration and PID tuning is crucial to control the nozzle temperature and avoid the nozzle clogging. Temperature calibration and retraction settings should be adjusted before printing to prevent the fused filament from solidifying inside the nozzle while moving. In addition, nozzle height calibration is necessary to deposit the nozzle at the correct place relative to the build plate, which can avoid the extruded filament being squashed or dragged.

The Dual Force V2 (Upgrading 3D Printing Machine with Cooling System)

The research has so far conducted multiple experiments using plastic filament and modified the cooling system to demonstrate the printable nature of these lattice configurations. It became evident after numerous tests that the two blowers were not producing enough cooling to perform the necessary work. Therefore, the researchers upgraded the extruder to a Dual Force V2, of which the main feature is providing compressed air from a tank using copper pipes. With this feature, it is possible to avoid cooling the hot-end during extrusion of the plastic. The new copper pipes allow for angle adjustments and focus the air on the extruded material rather than the hot-end. This upgraded cooling system made it possible to control air volume in each pipe, which was especially useful when working with the PET and TPU materials at the same time, as they require two different temperatures to achieve cooling. The main improvement of the updated Dual Force V2 was the cooling system, changing from one fan to two fans, which increased cooling efficiency and reduced cooling time. The cooling system with one fan was not enough to control the cooling air and cool down the extruded plastic immediately, causing the extruded fused material to not be rigid enough to be shaped in the printing panel. The Dual Force V2 was equipped with two fans after upgrading the cooling system with blowers, so both plastics could be fused fully before being extruded. Also, after extrusion from the hot-end, the two blowers could accelerate the cooling speed, transitioning the fused plastic to rigid material immediately, allowing it to be shaped well in the printing panel.

4.3. Robotic Fabrication Tests

The researchers designed and built a dual filament extruder, aiming to print two types of materials and achieve gradation from material A to material B. TPU and PET were mainly used, which required different speeds and temperatures as the dual filament to achieve the combination of materials.

Test Results with Dual Force V1 (Before Upgrading Cooling System)

First, the researchers undertook several fabrication tests of the speed of the filaments and the temperature settings in order to achieve a complete print. Figure 22 displays some robot fabrication results affected by the program speed, nozzle temperature, target waiting time, and stepper motor settings. Due to the Dual Force V1's poor temperature management, the extruded filament could not be cooled down in time, which resulted in uneven printed material.

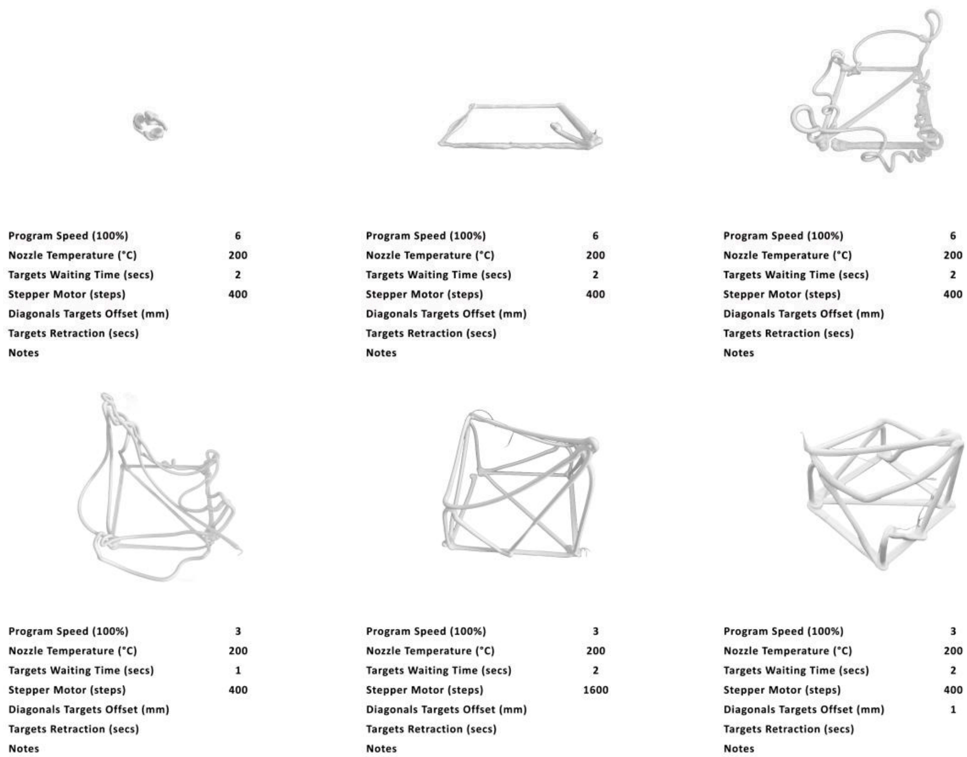
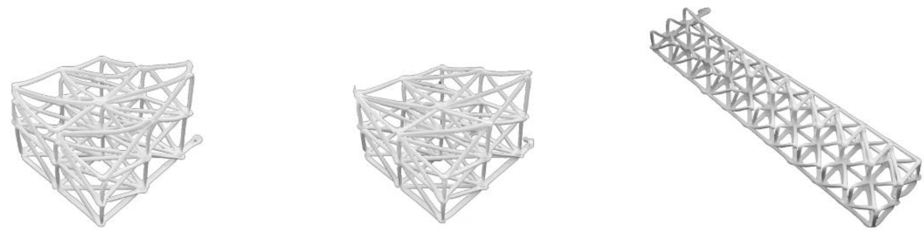


Figure 22. Test results and settings with Dual Force V1 (before upgrading cooling system).

Test Results with Dual Force V2 (After Upgrading Cooling System)

After upgrading the cooling system from the Dual Force V1 to the Dual Force V2, the test results improved. With the help of the two-fan cooling system, it was possible to print intricate large-scale models by cooling down the extruded filament immediately. As seen in Figure 23, the test results achieved the completion of large, tall, and straight printed material. It is clear that, compared to the test results with Dual Force V1, the printing results with Dual Force V2 have more accurate and rigid shapes, multiple and higher layering, and better bond strength because the extruded material can be cooled down immediately in open air and bonded closely.



Program Speed (100%)	4	Program Speed (100%)	4	Program Speed (100%)	4
Nozzle Temperature (°C)	200	Nozzle Temperature (°C)	190	Nozzle Temperature (°C)	190
Targets Waiting Time (secs)	15	Targets Waiting Time (secs)	15	Targets Waiting Time (secs)	15
Stepper Motor (steps)	400	Stepper Motor (steps)	400	Stepper Motor (steps)	400
Diagonals Targets Offset (mm)	5	Diagonals Targets Offset (mm)	5	Diagonals Targets Offset (mm)	5
Verticals Targets Offset (mm)	3	Verticals Targets Offset (mm)	3	Verticals Targets Offset (mm)	3
Notes		Notes		Notes	

Figure 23. Test results and settings with Dual Force V2 (after upgrading cooling system), which achieved large-scale and rigid printed models.

Test Results with Multi-Material Gradation

The next stage of the experiment involved multi-material gradation achieved by dual-filament extruder. By setting different parameters for motor 1 and motor 2, the aim was to achieve different gradations. In this experiment, the robot was given different sets of commands, as illustrated from Set 1 to Set 5.

Set 1: Motor 1 working at 100% and Motor 2 at 0%

Set 2: Motor 1 working at 75% and Motor 2 at 25%

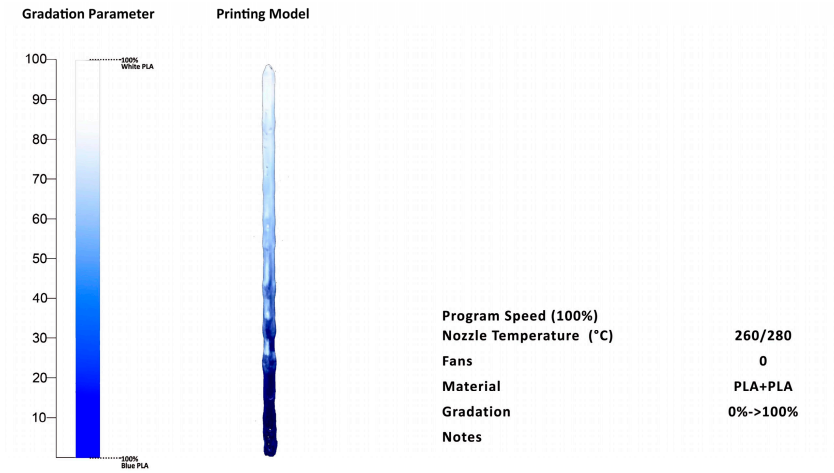
Set 3: Motor 1 working at 50% and Motor 2 at 50%

Set 4: Motor 1 working at 25% and Motor 2 at 75%

Set 5: Motor 1 working at 0% and Motor 2 at 100%

This first test started with 100% blue PLA and ended with 100% white PLA, controlling the nozzle temperature at 260 °C to 280 °C. The area in the middle formed a gradation. The printing result and parameter settings are presented in Figure 24A. Another test aimed to alternate between blue and white by setting a different Divide parameter. The printing result and Divide parameter settings can be seen in Figure 24B.

The robotic printing approach enables complex toolpaths and multi-material blending, resulting in greater material deposition accuracy and creating more flexible and intricate geometries. Nevertheless, the experiment indicates that it also faces limitations such as slow printing speed, long printing time within complex geometries, and limited build size affected by the reach or workspace of the robot. There are also challenges facing robotic performance in terms of the range of printable materials, which commonly focuses on PLA filament at present and does not extend to other kinds of material. Further research and development are still needed to overcome these limitations and explore the full potential of robotic printing in various applications.



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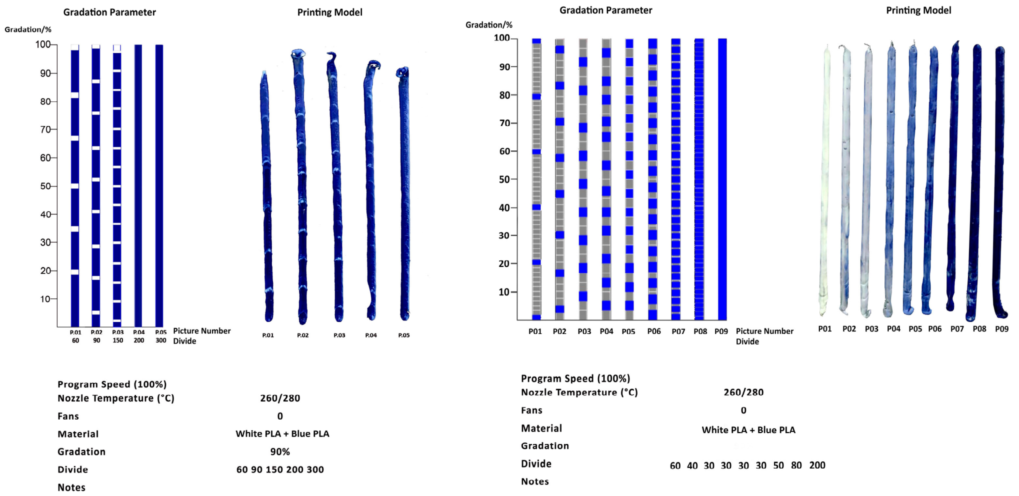


(**B**)

Figure 24. (**A**) Gradation tests and parameter settings with blue PET and white PET. (**B**) Gradation tests and Divide parameter settings with blue PET and white PET.

5. Application of Fused-Space Design in Architecture

5.1. Typology Design of Fused Space

The fused-space design concept is based on Adolf Loos's Raumplan [31], which refers to a spatial solution based on each room, rather than an area by the floor. Its trademark is a dramatic gradation in the height of the individual rooms according to their functions. Therefore, rooms in fused-space design are assembled according to function and achieve the maximum use of the interior space. The properties of the designed fused space can be divided into light perception and privacy of a space, controlled by the density and transparency of the enclosure, which is achieved via the above-mentioned digital algorithms.

Therefore, the fused-space typology design process starts with space requirements by setting sphere spaces as needed in a solid cube with a structure core which is made of concrete, then through sphere inflation and applying a Boolean methodology to the solid cube, finally generating the space enclosure. Next, the digital algorithms are applied to the space enclosure and obtain the design result. Taking the structure into consideration, the primary steel structure was positioned between the sphere gaps because the plastic is currently insufficiently robust to support the entire building. Therefore, the final design model is composed of three main parts: the steel support structure, the Voronoi enclosure with multi-material, and the sphere shell.

5.2. Fused-Space Design Application at London Test Sites

The design application aimed to find vacant spaces in London to implement the fused-space design methodology. There is a noticeable quantity of vacant space in London between modernist buildings. The study finally chose Stangate House, the Alexandra and Ainsworth Estate, and the Barbican Estate as the main test sites, to validate the improvement of space quality through model simulation algorithms.

Stangate House

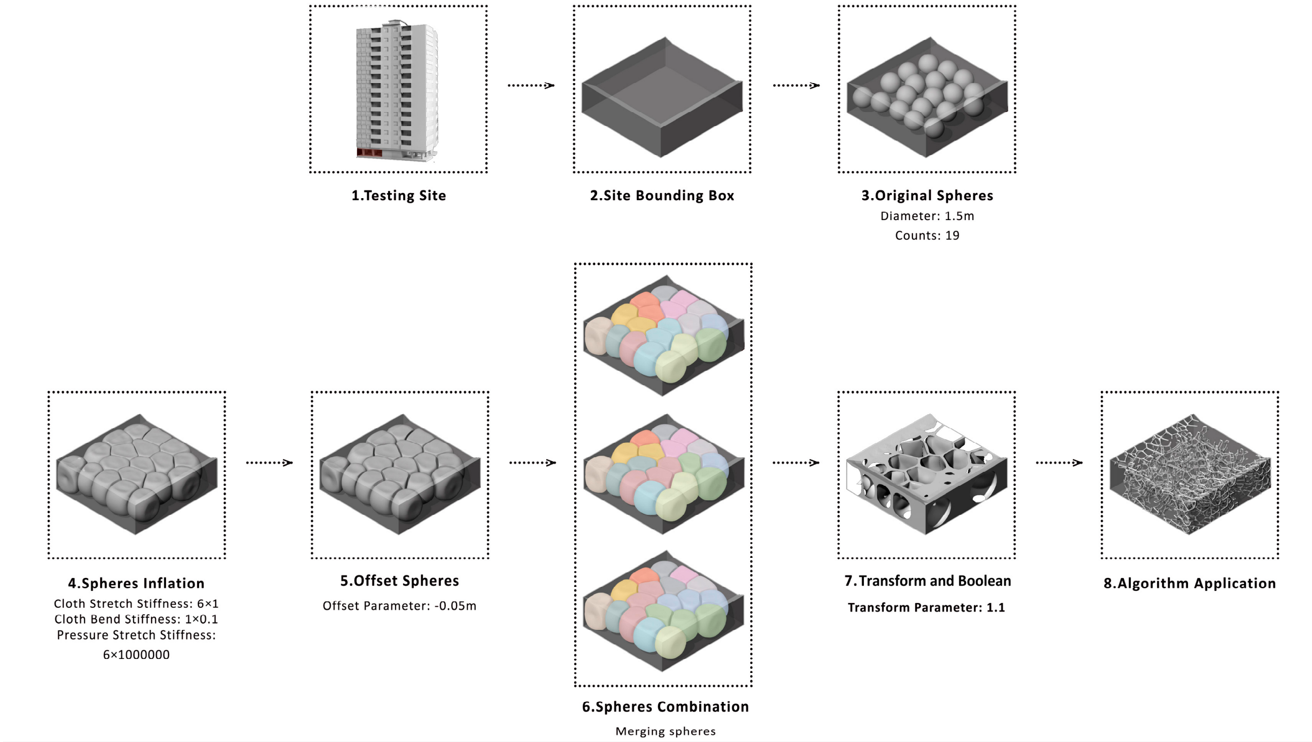
Stangate House is a residential building across from St Thomas' Hospital, which is in the center of London and a busy area, with large amounts of passers-by. The intended design space is the area under the elevated ground floor. Its four borders are exposed to the outside world, and there are always people sitting or standing on the ground terrace. In the design process, space spheres were set in the site's bounding box first, and through sphere inflation and applying a Boolean methodology to the boundary, the space enclosure was obtained, which would be defined by algorithm application. The spaces were confirmed by spheres and separated by digital enclosure with density and transparency gradation. Figure 25A shows the detailed design process.

Through the fused-space design in Stangate House, the area under the elevated ground floor, which is dark and obscure with a height of less than 3 m, could be transformed into an appealing display area with a variety of spatial properties. By using multi-material and setting sphere spaces as needed, transparent enclosures and new flexible space separations can be created. As illustrated in Figure 25B, the model simulation result confirms that the previous single-function space can be transformed into nine sphere rooms with distinct functions, which allow for programmatic flexibility validated by spatial adaptability metrics. Additionally, the model simulation results with transparency can be seen in Figure 25C; the new designed space enclosure is simulated with plastic multi-material instead of traditional concrete or bricks. The transparent area can be embedded in the facade facing the sun, ensuring an inner space with sufficient insolation. While user feedback was not collected due to the conceptual nature of the project, environmental performance was simulated using daylight analysis, showing a 42% increase in average insolation levels compared to enclosing the space under the elevated ground floor with concrete.

Alexandra and Ainsworth Estate

Test site 2 is the Alexandra and Ainsworth Estate, built between 1972 and 1978, which is an area of collective housing with high-density living. The long, linear, low-rise buildings were constructed of heavy concrete and had low, gloomy interior spaces with the same height. The goal of the design was to create a new vertical building with varying-height spaces on the empty square area in the northwest corner of the estate and the vacant roof area, which would provide more common space and programs for the whole community. The vertical building was created using Adolf Loos's Raumplan [31], which combines internal space with a striking height gradation based on function requirements.

As seen in Figure 26A, once the bounding box was confirmed, sphere spaces could be set. Then, through inflation and applying the Boolean methodology to the boundary, a final enclosure was obtained, to which the Voronoi algorithm could be applied. Figure 26B displays the simulation result of the final design. The use of multi-material for the enclosure of the rooms results in a colorful atmosphere. The separation walls between interconnected spaces are generated with different levels of transparency and porosity, resulting in different space viewability rates of 0% to 70%. The model simulation is also equipped with adaptive sphere room count and room size, ranging from 3 m high to 10 m high, satisfying different user performance requirements and validated by spatial adaptability metrics.



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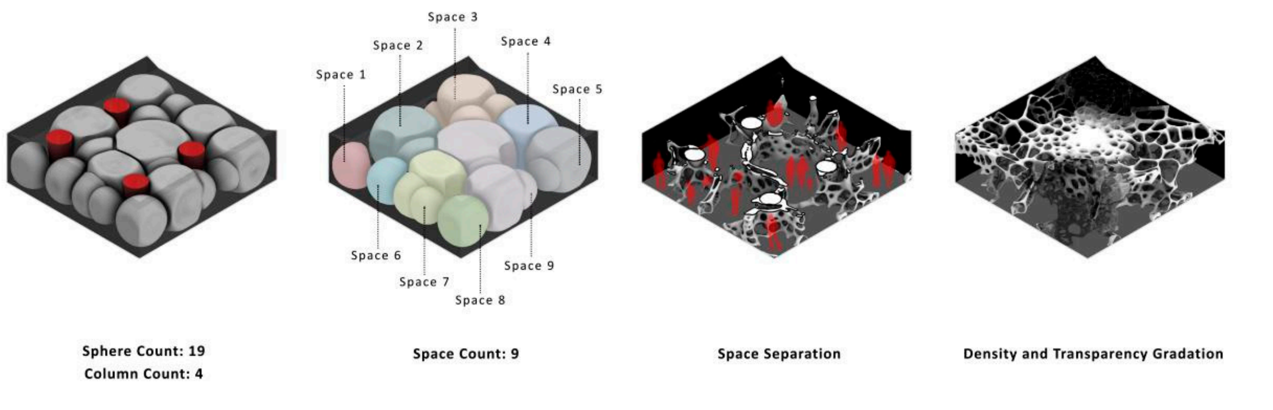

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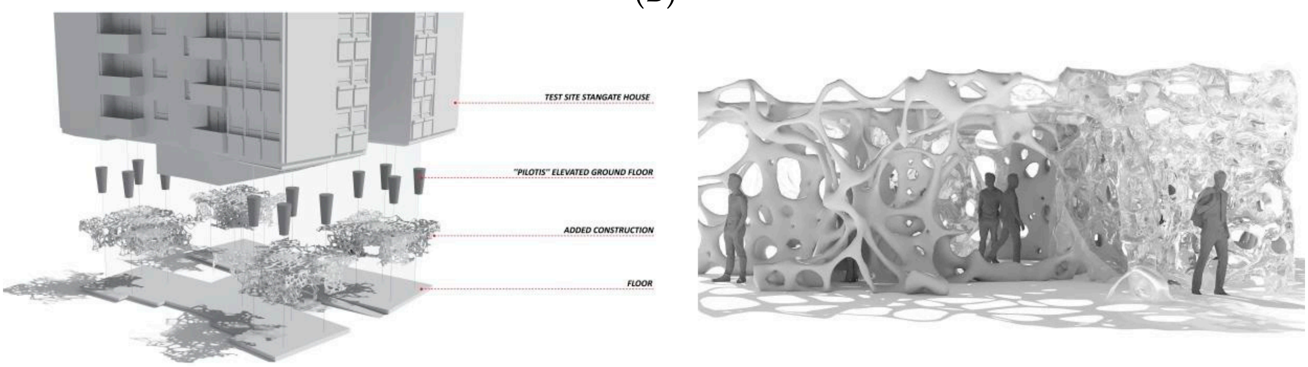
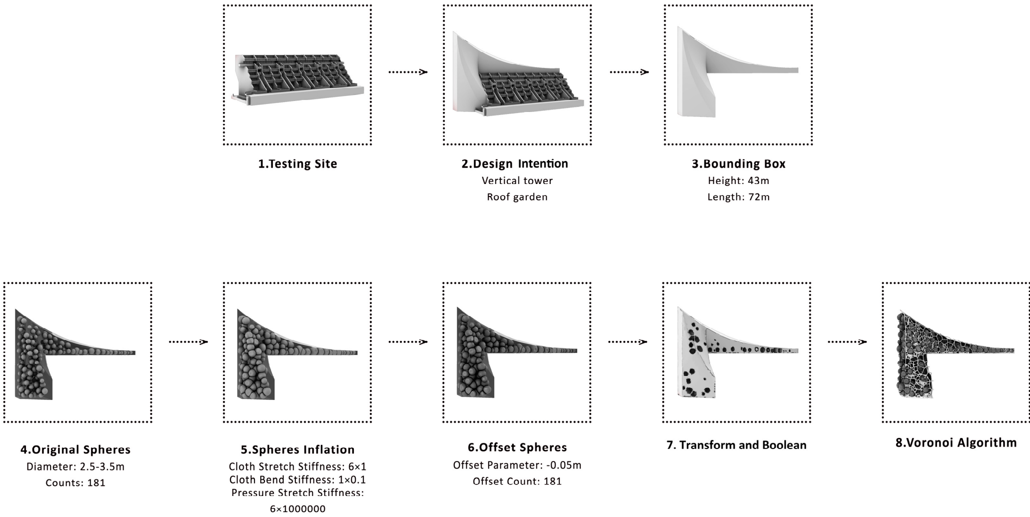


(**C**)

Figure 25. (**A**) Digital design process for Stangate House; (**B**) flexible space separation simulated in the design, transforming a single space into nine rooms with distinct functions; (**C**) fused-space enclosure simulated with transparency gradation.



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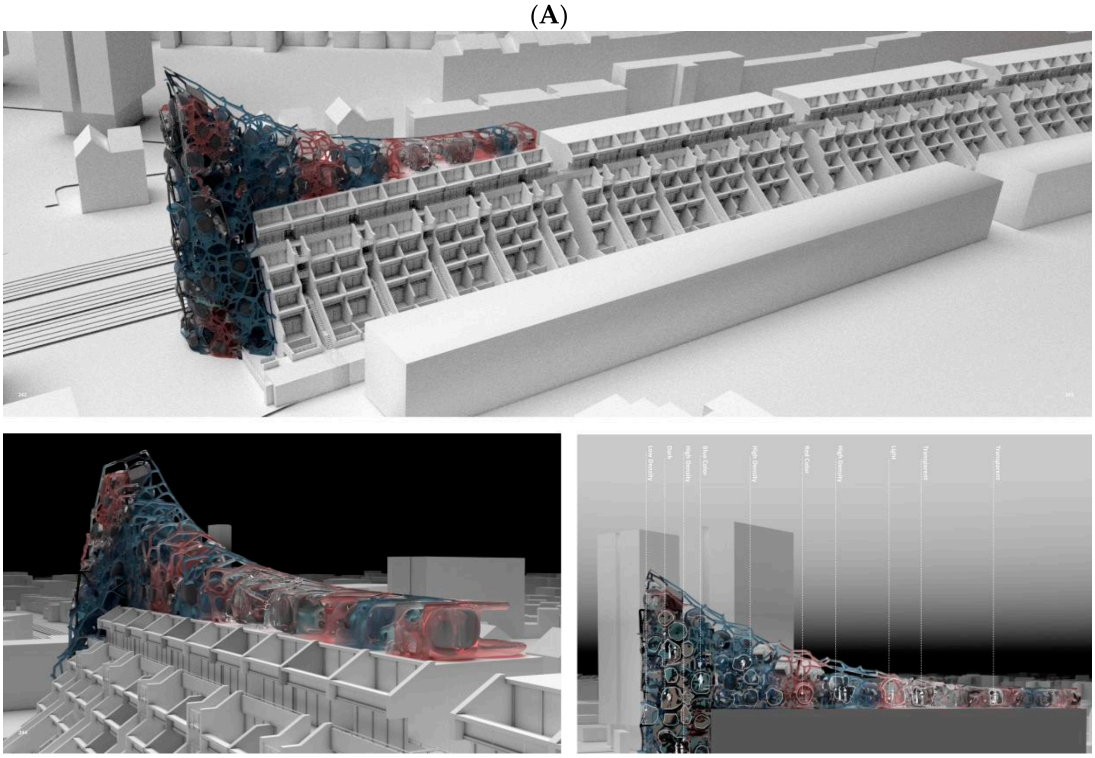

(**B**)

Figure 26. (**A**) Digital design process for the Alexandra and Ainsworth Estate; (**B**) simulation model of fused-space design for the Alexandra and Ainsworth Estate with different space viewability rates and adaptive sphere room count and room size.

Barbican Estate

Test site 3 is the Barbican Estate, which is a residential and cultural complex in the center of London. It is a fantastic location for ceremonies and other communal cultural events, with plenty of open corridors and terraces that offer the opportunity to reuse and create new program spaces. In the Barbican Estate, the design focuses on a small building attached to a corridor and its roof space, aiming to create a continuous space by combining the vacant terrace and roof. Therefore, the bounding box is attached to the building and extends to the roof.

As displayed in Figure 27A, spheres were set in the defined bounding box, through sphere inflation and applying the Boolean methodology to the boundary to obtain the space enclosure, which could be generated by the Voronoi algorithm. Figure 27B shows the final fused sphere spaces simulated with the Voronoi enclosure. The original empty corridor and roof have been outfitted with a multi-material scheme that offers variable room count and room size, ranging from 3 m high to 15 m high, allowing for programmatic flexibility. The manageable porosity and transparency of enclosure ensure changeable wall viewability rates of 20% to 80%. Consequently, the new design application offers more adaptive space functions with different viewability, and room size and count, aiding in the repurposing of the Barbican Estate's unoccupied space.

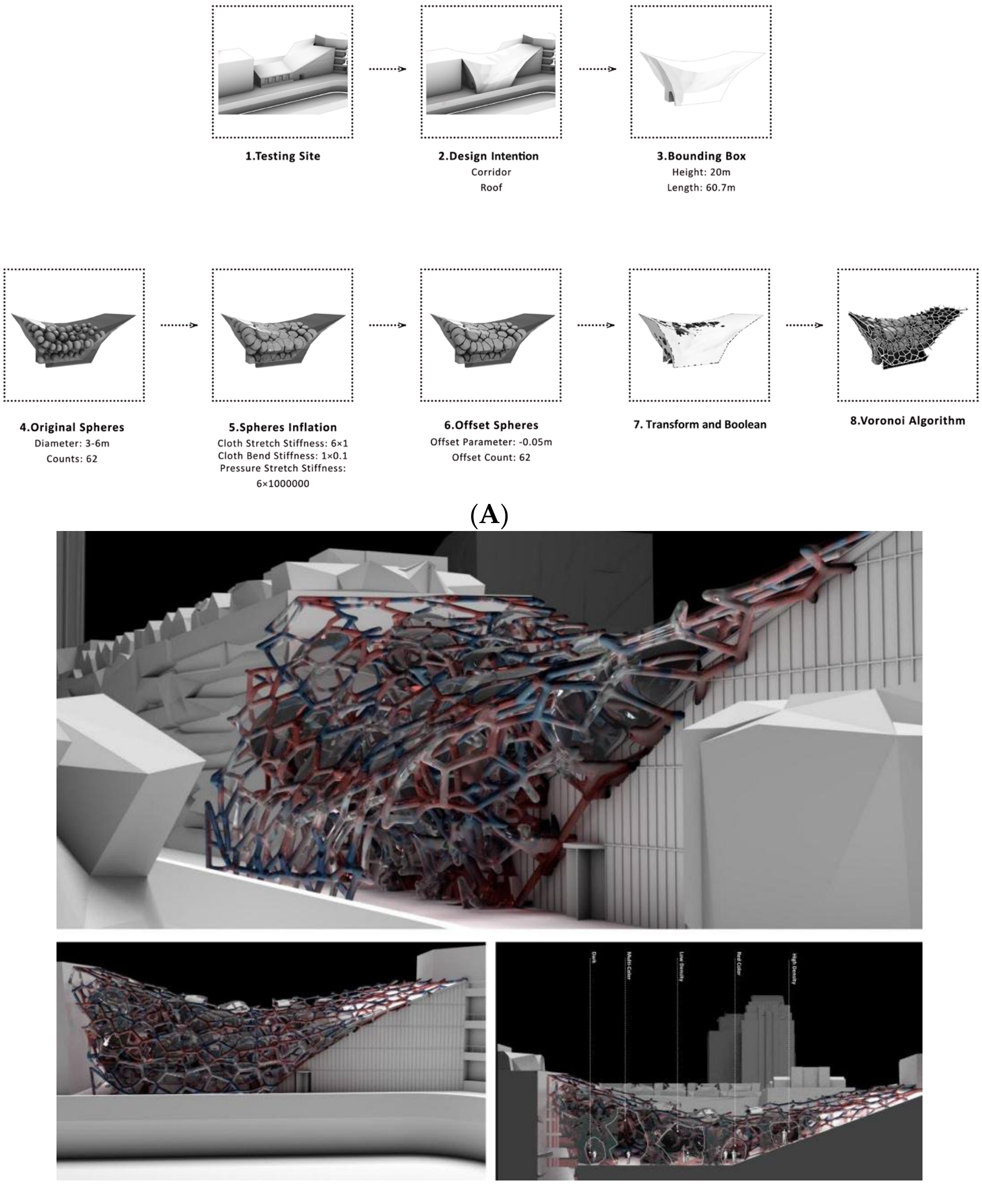

Figure 27. (**A**) Digital design process for the Barbican Estate; (**B**) simulation model of fused-space design for the Barbican Estate with different viewability, and room size and count.

6. Discussion

This research addresses the era of multi-material, which could have a profound impact on architectural evolution. Multi-material architecture is a logical progression of contemporary manufacturing capabilities, rather than a nostalgic trend explored by architects and researchers. The plastic property tests and fused experiments conducted in this study demonstrate the potential of utilizing recycled multi-material in fused space, stimulating new design styles and aesthetic thinking. Three-dimensional printing and robotic fabrication tests, along with the upgraded Dual Force machine, successfully print large-scale objects, promoting intelligent construction in architecture and printing techniques with multiple plastics. Additionally, the application of fused-space design at the test sites demonstrates how multi-materials can contribute to the formation of variable and flexible spatial qualities.

The use of recycled plastic in fused architectural space facilitates the recycling of waste materials, which could have a substantial environmental impact on building urban resilience and low-carbon cities by reducing energy consumption. However, it is crucial to consider the volatile organic compounds (VOCs) and particulate matter (PM) emissions generated during 3D printing, which have potential effects on indoor air quality and human health. In addition, the long-term durability of 3D printed parts varies from 1 to 10 years depending on the material type, infill density, UV exposure, and temperature fluctuations, which still need further research to extend the lifespan of 3D-printed products.

Furthermore, there is still considerable progress to be made in exploring the use of plastic multi-material in building construction. For instance, when considering structural support, plastic is not strong enough for high-rise building construction. Currently, it is necessary to rely on metal or concrete structures, ensuring proper integration between the plastic enclosure and the primary structural support. Another challenge is the fire safety of plastic. Additionally, more research is required to develop long-lasting fire protection coatings for plastic, ensuring the creation of strong and durable buildings. Moreover, the robotic fabrication process is currently limited to laboratory testing, and the 3D printing of large-scale fused spaces in real-world locations requires further research and updates to fabrication machines.

7. Conclusions

This study presents a comprehensive design-to-fabrication workflow for creating fused architectural spaces using recycled plastic-based multi-material. The research demonstrates that PET and TPU, two commonly discarded plastic types, can be transformed into functional architectural enclosures through robotic 3D printing using dual-extrusion techniques. The integration of algorithmic design methodologies, including sphere packing and nature-inspired forming algorithms like Voronoi, Swarm Behavior, Shortest Path, and Game of Life, enables the generation of complex spatial geometries tailored by material gradation parameters—namely thickness, transparency, density, and flexibility.

Experimental results confirm that multi-material gradation can be successfully achieved through controlled extrusion rates and adaptive cooling systems, as evidenced by the Dual Force V1 and V2 prototypes. The real-world applicability of the system is further validated by the simulation of fused-space prototypes in three urban sites in London, each showcasing distinct spatial properties and environmental responses.

In conclusion, this research offers a replicable and sustainable approach to multi-material reuse and space-making, addressing key challenges in architectural waste reduction, digital fabrication, and spatial customization. Despite its potential, the scalability of fused-space design is currently limited by the speed of robotic extrusion, build size of robotic fabrication, and integration with structural systems in urban-scale construction. Future development will focus on on-site modular fabrication, lightweight structural cores, and compliance with urban fire safety regulations to facilitate wider adoption. With further development in structural integration, fire safety, and large-scale deployment, fused-space design holds strong potential to reshape the future of resource-efficient and materially expressive architecture.

8. Related Similar Works

This study mainly focuses on the application of recycled plastic multi-material and robotic 3D printing in architectural fused space, and also collects previous similar works about recycled plastic, multi-material, and 3D printing technologies, listed below in Table 1.

Table 1. Related similar works about recycled plastic, multi-material, and 3D printing.

Research Title	Author(s)	Year
Automated Multi-Material Fabrication of Buildings	da Silva Craveiro, F. G. [32]	2020
Towards design of mechanical part and electronic control of multi-material/multicolor fused deposition modeling 3D printing.	Boulaala, M., Elmessaoudi, D., Buj-Corral, I., El Mesbahi, J., Ezbakhe, O., Astito, A., . . . & El Mesbahi, A. [33]	2020
Fused deposition modelling approach using 3D printing and recycled industrial materials for a sustainable environment: a review.	Madhu, N. R., Erfani, H., Jadoun, S., Amir, M., Thiagarajan, Y., & Chauhan, N. P. S. [34]	2022
3D printing in upcycling plastic and biomass waste to sustainable polymer blends and composites: A review.	Hassan, M., Mohanty, A. K., & Misra, M. [35]	2024
A Systematic Review of Innovative Advances in Multi-Material Additive Manufacturing: Implications for Architecture and Construction.	Fakhr Ghasemi, A., & Pinto Duarte, J. [6]	2025

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