Pinnacle Academic Press
Proceedings Series

Vol. 4 2025

Article **Open Access**

The Evolution of Modernist Architecture through Recycled Multi-Material and Digital Algorithms

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Received: 30 April 2025
Revised: 13 May 2025
Accepted: 08 June 2025
Published: 20 July 2025

Abstract: Modernist architecture emerged as a response to basic social needs through the social housing movement and represented a significant experiment in urban living, particularly in cities like London. A detailed analysis of modernist architecture from space, social, material, and economic aspects reveal numerous issues, including poor space quality, limited privacy, and inefficient as well as costly use of materials. Therefore, recycled multi-material and digital algorithms were applied to reclaim vacant spaces and enhance space quality in these architectural environments. Using digital algorithms, multi-materials composed of recycled plastics can be 3D printed with variable gradients in thickness, density, transparency, and flexibility. These material gradations are generated by digital analysis of structure, porosity, privacy, and daylight based on space openness, privacy, structural strength, and daylight access requirements, which were introduced to enhance space quality and resolve specific space issues. In the end, Stangate House, Alexandra and Ainsworth Estate were selected as test sites, where multi-material and digital algorithms were implemented in vacant spaces to support the evolution and revitalization of heritage-worthy modernist architecture.

Keywords: modernist architecture; vacant space; recycled plastic; multi-material; digital algorithms; gradation parameters

1. Introduction

Modernism first emerged in the 1920s and received widespread acclaim after the Second World War [1], which aimed to solve the urban living problems and accelerate industrialization and social changes. The modernist architects emphasized the purity of the form. "Form follows function" is frequently employed, which means the quality of fulfilling a purpose directly, without any wasted effort [2]. Meanwhile, the new material also stimulates the invention of structure system, such as the long-span steel trusses provide the possibility for flexible column-free space, which results in the open, flowing interior space. Walls, doors, and hallways no longer define and separate the room space. Living, dining, and kitchen areas often flow together as a continuous interior space. Windows were replaced by large expanses of floor to ceiling glass, affording stunning vistas and introducing natural sunlight deep into the inside of rooms.

However, modernist architectures are becoming increasingly problematic over time [3], which are regarded as imposition, dogmatism, intolerance, categorization, oversimplification [4], that's why the Heygate Estate was demolished easily and the Aylesbury Estate is undergoing a regeneration program. Modern architecture has many space issues, such as excessive direct light or inadequate light perception; Long, dull, rigid space with no variation; low, gloomy, uninviting interior space with all the same height. As claimed by Le Corbusier as the five points of modernist architecture [5], modernist architectures usually are supported by "pilotis" with a free design of ground floor [6], which nowadays often appear as low, dark, damp, messy, and lacking natural light. Besides, modernist architects declared Less is more [7], the shape of modernist building is based on simple geometries like cube, box, spheres. The interior plan is always rectangular with a long, dull edge without varieties and clear separation to define a founctional space. The low height of the space also creates the depressed and uninviting space quality. In addition to space issues, modernist architecture includes social issues as well, such as privacy invasion and large areas of unoccupied, unsafe communal space. Communal public areas were designed to increase the social interaction, but people don't have a strong sense of social responsibilities and community lack of rational management measures, the communal area became dysfunctional, turning into unpleasant and unsafe areas. The modernist architects also failed to finish separating the public and private spaces in order to create a flowing, open room and highlight the communal areas [8], resulting in a great deal of confusion and chaos. Additionally, mass production of buildings has turned out to be more costly than conventional technology, and often much less efficient and durable. The extensive use of glass material caused terrible energy efficiency, which need more energy to enhance human comfort. Concrete and steel were commonly used in a simplified way to create flat floor and vertical walls [9], which is stiff and not flexible. Recent developments in digital modeling and interactive systems—originally emerging in manufacturing—have provided novel frameworks for rethinking material combinations, form generation, and responsive design [10]. Similarly, intelligent coordination systems can potentially optimize architectural workflows, improve modular efficiency, and reduce waste, offering new paths for post-modern architectural innovation [11].

Due to the space, social, and material issues, a growing number of modernist structures were abandoned and demolished from 1970s [12]. Instead of demolishing them, reusing these typical historic architecture can avoid the waste of material and is beneficial to environment sustainable development. Modernist building is special for the concrete columns, steel frame, removable walls [11], which ensured their stability and possibility to be changed. This research intends to reclaim the wasted space and communal area in modernist architecture and create better space quality by using recyled multi-material [13] via digital algorithms. Plastic pollution has become one of the most pressing environmental issues and exerts an adverse effect on ecosystems as a whole [14]. Reusing waste-based plastic materials can significantly improve the environment by reducing greenhouse gas emissions and prolonging building lifespans [15,16]. Multi-material refers to the combination of variable materials with significantly different properties, which is a useful tool to discover new design ways not only on complex geometries but also arbitrary distributions of materials within those geometries [17]. Plastic multi-material is easily reformed, blended, 3D-printed, and applied in digital design applications [18,19]. Two commonly used and recycled plastics, PET and TPU, were examined in the study, which can create varying degrees of opacity, color, texture, and rigidity by blending. Additionally, the recycled multi-material design can be integrated with digital computation, such as using circle packing and sphere packing algrithms to define new functional spaces; applying Voronoi algorithm to generate the space enclosure and reclaim the vacant space; engaging digital analysis such as structure, porosity, privacy, and daylight analysis to enhance spatial qualities through multi-material gradation and distribution on thickness, density, transparency, and flexibility [20-22].

2. Multi-Material and Digital Design Methodolgy

2.1. Reclaiming Vacant Spaces in Modernist Architecture through Recycled Multi-Material and Digital Algorithms

Given that plastic is a major contributor to the imbalance of ecological system, reusing and recycling used plastic in construction contributes significantly to a sustainable environment. The research aims to recycle plastic and use it in the construction industry, with the aim of reclaiming vacant spaces and addressing spatial problems in modernist architecture. Plastic materials with different features, including different colors, textures, stiffness, insulation, and gradations, can be combined to create a multi-material with high performance.Two widely available recycled plastic types—polyethylene terephthalate (PET) and thermoplastic polyurethane (TPU)—with distinct properties were selected in this research. By blending transparent PET and flexible TPU, a hybrid material was produced that transitions between clear and opaque, and between rigid and flexible, which can be used to create spatial variation and can be 3D printed using digital algorithms.

Furthermore, to reclaim vacant space in modernist architecture, the strategy is to introduce public, vibrant, and inviting programs—such as community events, shared workshops, or social lounges—that can activate the space and encourage interaction. Once new activities are introduced, new space separation needs to be formed. To generate appealing and adaptable space separations, digital algorithms like circle packing in 2D and sphere packing in 3D were employed. These algorithms produce diverse spatial combinations in confined areas. Circle packing algorithm assists in defining space layouts by adapting to various boundary conditions and different combinations of circle radius and quantity. Meanwhile, the sphere packing algorithm aims to generate fixed-size spatial units by regulating sphere volume, number, and dynamic interactions such as gravity and collision. Once the space volumes are defined through packing algorithms, the Voronoi algorithm is applied to generate the enclosing structures that adapt to the spatial divisions, enhancing the spatial experience. Voronoi diagram is a straightforward division of a given collection of n points into n regions where each point in each cell is closer to a particular point from the set of n points than the other n-1 points [22]. By regulating the points and rule settings, it can be achieved to adjust space enclosure with variable densities and degrees of porosity.

2.2. Enhancing Space Qualities through Multi-Material Gradation and Distribution

After the space enclosure is generated by digital algorithm including circle packing, sphere packing and Voronoi, multi-material gradation can be applied to the enclosure, creating variable space qualities. Multi-material exhibits variable properties through the blending of different material types, enabling compatibility with 3D printing technologies and digital computation. The thickness, density, transparency, and flexibility gradation of multi-materials can be generated by structure, porosity, privacy, and daylight analysis, which has the ability to guide the distribution of multi-materials, enhancing space qualities that are adaptive to different functional requirements.

Thickness gradation

The thickness gradation of multi-material is influenced by structural analyses. The Karamba plugin in Grasshopper was used to analyze the structural behavior of the prototype by inputting the load and tension parameters. Areas with higher structural loads exhibit higher thickness and material density. By applying structure analysis algorithm, a color gradation will be generated to visually express variations in thickness across the structure. This color gradation can then be integrated into space enclosure formed by Voronoi algorithm. As seen in Figure 1, multi-materials are distributed according to color-coded zones, and the prototype enclosure exhibits thickness variations corresponding to the color gradation. This thickness gradation strategy can be implemented in the building construction process to optimize material usage and enhance structural strength.

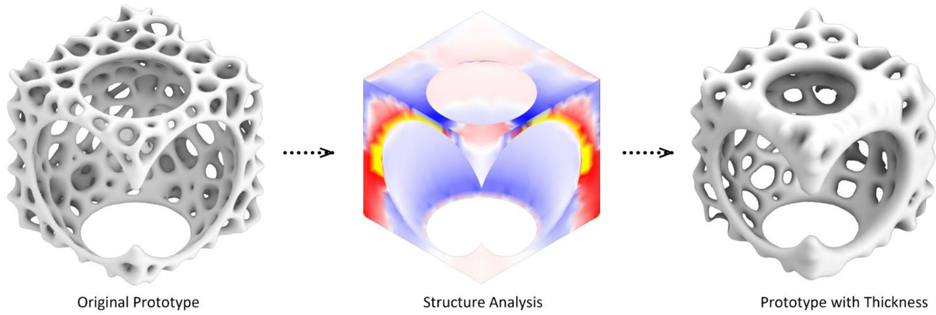

Figure 1. Thickness gradation generated by structure analysis in "karamba" plugin.

Density gradation

The Voronoi algorithm can generate different density gradations and is widely used in the digital design process. The density gradation is closely related to space privacy requirements. In the spaces intended to be more open to the exterior, the space enclosure can be digitally generated with lower density. Conversely, space enclosure with higher density can be applied to enclose more private spaces. Figure 2 illustrates gradually changed patterns and density in the formed space enclosure controlled by digital Voronoi algorithm, effectively representing the distribution of material and creating variable space privacy.

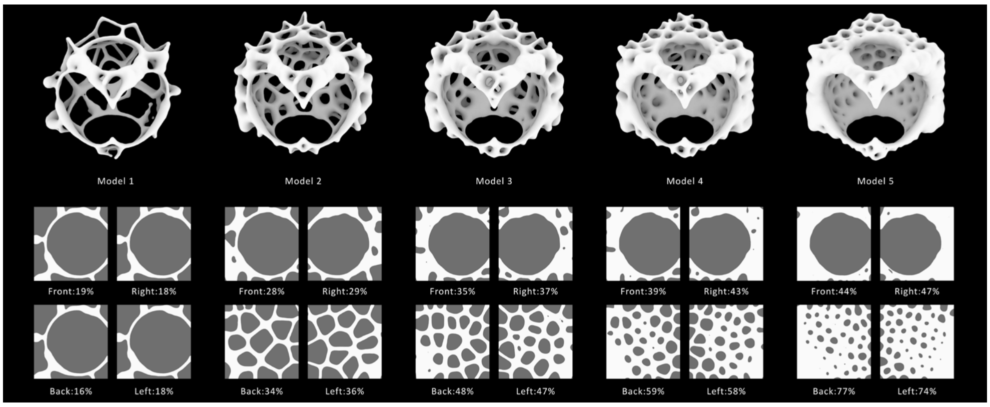

Figure 2. Density gradation controlled by digital Voronoi algorithm, representing the distribution of material and creating variable space privacy.

2.2.1. Transparency gradation

The transparency gradation is affected by the amount of incident radiation on the site. Digital analysis using the Ladybug plugin in Grasshopper enables the generation of daylight diagram at specific site. Subsequently, multi-materials with variable transparency properties are distributed based on the daylight parameters. In areas with higher levels of daylight, greater transparent multi-materials are distributed to ensure receiving adequate natural light and to create a brighter space quality. The transparency gradation in the space enclosure design corresponds to the incident radiation color gradation. In this research, specially selected multi-materials composed of PET and TPU are applied to achieve a continuous gradation from transparent to opaque. As presented in Figure 3, by blending these two materials, the space enclosure shows apparent gradation from transparent to opaque regions according to incident radiation color gradation.

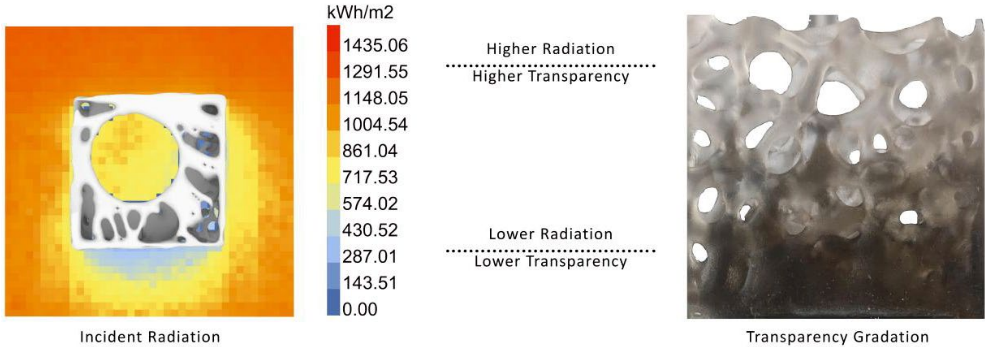

Figure 3. Transparency gradation related to incident radiation color gradation.

2.2.2. Flexibility gradation

Flexibility gradation can be generated in Grasshopper by adjusting the ratio of two materials according to the degree of spatial openness required—more open spaces use a higher proportion of flexible material. When the flexible material is embedded into the rigid space enclosure, it functions as an interactive medium between two spatial zones. This component can be defined as a door or window, stimulating social communication and providing access to the exterior. The higher the proportion of flexible material, the more open the space becomes to the external environment, resulting in reduced privacy. The gradation between flexible and rigid materials shows the transition from public to private space. In Figure 4, hard PET and flexible TPU were blended to produce a high-performance multi-material with flexibility gradation, which illustrates the space openness transition.

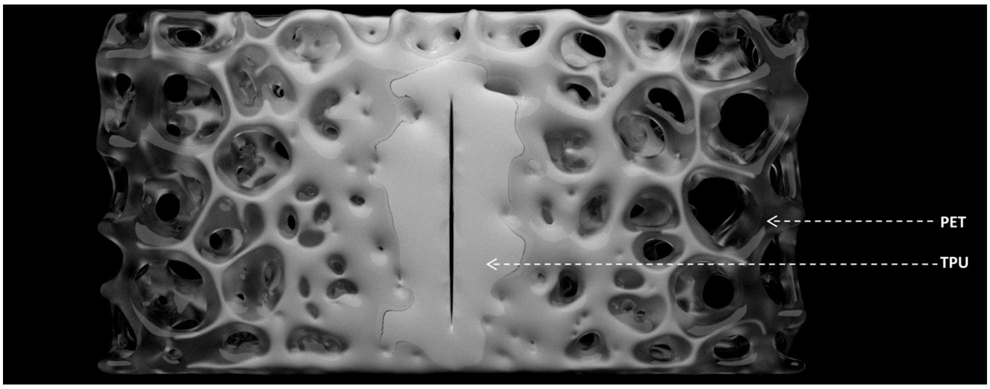

Figure 4. Flexibility gradation by blending hard PET and flexible TPU illustrating the space openness transition.

2.3. Resolving Modernist Architecture's issues through Multi-Material Design

Most of the spaces under elevated buildings in modernist architecture suffer from insufficient natural light. To solve this issue, multi-material enclosures with varying transparency gradation can be designed based on light recieving requirements by blending transparent PET with opaque TPU. By controlling the distribution of multi-materials with transparency gradation, the entry of natural daylight into the space can be adjusted. Transparent materials effectively enhance the deep penetration of natural daylight into indoor spaces, which improves the dark and damp space quality in modernist architecture. On the other hand, as shown in Figure 5, in spaces where daylight is undesired, the opaque TPU part and higher density enclosure of the multi-material can effectively prevent natural daylight.

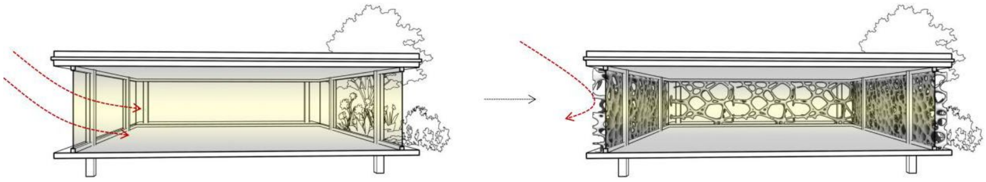

Figure 5. Before: Excessive direct light; After: Apply multi-material enclosure with opaque TPU part and higher density.

As for the long, dull, stiff spaces lacking variation, space enclosures with varying densities can be designed with multi-materials. Multi-material separations can be generated through digital computation and fabricated via 3D printing. Digital algorithms enable the generation of curved enclosures with variable patterns and density. The form, size, and density of the enclosure can be precisely controlled using parametric inputs in algorithmic modeling. Additionally, the circle packing and sphere packing algorithms can provide amounts of space combination choices, increasing the variety of multi-material separations. As presented in Figure 6, the application of multi-material combined with digital algorithms can introduce the flexible and adaptable separations in long rectangular spaces, which introduces spatial diversity and functional variation within a limited area.

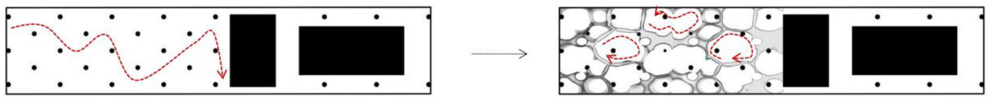

Figure 6. Before：Long, dull, stiff space lacking space variation; After：Introduce flexible and adaptable separations with multi-material.

To solve the issue of gloomy and uninviting spaces, colorful multi-materials can be designed by blending different types of plastics with variable colors to create vibrant and inviting space quality. Digital algorithms can generate variable textures and patterns, enabling the creation of inviting space enclosure and unique ornament. Through Voronoi algorithm, multi-material enclosure can be formed into variable curved shapes with changeable textures and patterns. Moreover, recycled plastics with various colors are commonly available, stimulating the creation of multi-material enclosures with color gradation without the need for additional dyeing processes through blending different plastics. Figure 7 shows the application of multi-material enclosure with innovative colors and forms in vacant depressed space in modernist architecture, which effectively enhance the space quality and create vibrant, inviting environment.

Figure 7. Before: Depressed, uninviting space environment; After: Apply multi-material enclosure with innovative colors and forms.

The low interior space with uniform height in modernist architecture shows great challenges in creating multiple space functions and public communal area with variable heights requirement. As illustrated in Figure 8, through sphere packing algorithm, various sphere spaces with different heights can be defined both within the interior and in the adjacent external areas of the existing architecture to increase space functions and program diversity. The enclosures of these sphere spaces are composed of multi-material, offering flexible forms and densities, providing adaptable space connections based on programmatic requirements.

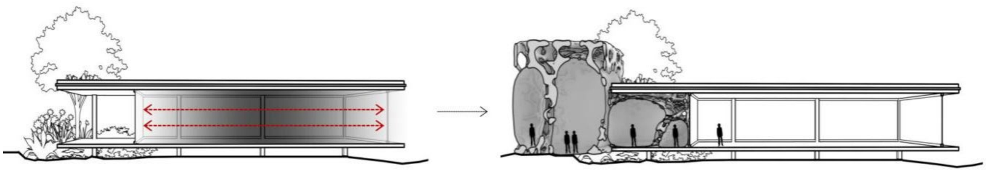

Figure 8. Before: Low inside space with uniform height; After: Make flexible space with variable heights using multi-material.

3. Results

3.1. Application on test sites

3.1.1. Stangate House

Stangate House was the first modernist architectural site where the design concept integrating multi-materials and digital algorithms was applied, which is a residential building located opposite St Thomas Hospital in center of London city. Stangate House is adjacent to a bus stop, providing it with high pedestrian visibility and interaction potential. The ground floor under elevated is open to the surrounding environment and interface directly with passersby, offering great possibilty to introduce activities and reclaim space programs. According to Le Corbusier's Five Points of Modernist Architecture, buildings are often supported by "pilotis," allowing for a free and open ground floor [5,6], with the main structure elevated above to liberate the ground floor. The open ground floor in Stangate House was initially designed for parks, transportation, circulation, and other functional purposes, but it is currently dark, deperessed, and without privacy, resulting in a vacant and underutilized area. By appllying sphere packing and Voronoi algorithms, new defined space with variable programs can be introduced to the ground floor. As shown in Figure 9, space enclosures and flexible separations with adaptable transparency and density between sphere spaces were generated through multi-material gradation, which enhance space qualities with adjustable light perception and privacy density, thereby revitalizing the historical building and transforming the previously vacant space into a functional environment.

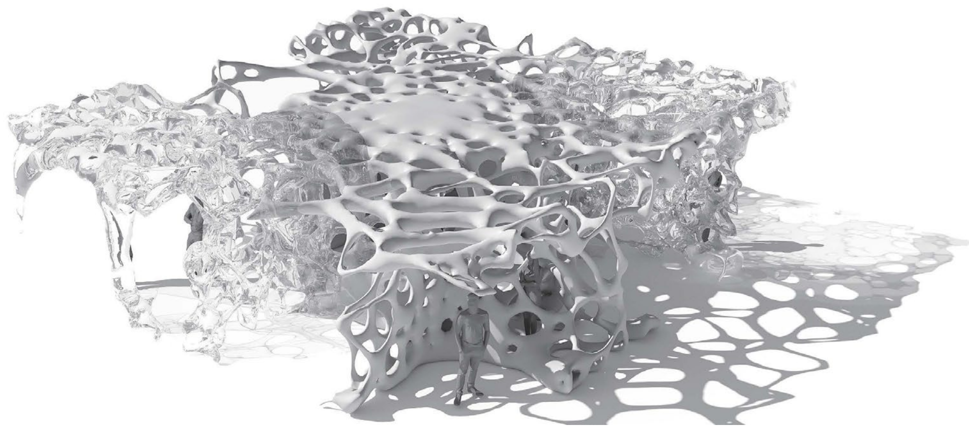

Figure 9. Space enclosures and flexible separations in ground floor of Stangate house.

3.1.2. Alexandra and Ainsworth Estate

Alexandra and Ainsworth Estate is a complex collective housing constructed between 1972 and 1978 in London, which is composed of long, linear, low-rise buildings with stepped sections. The buildings are constructed from heavy concrete and feature uniformly low ceiling heights. This results in confined and gloomy interior spaces that lack adaptable public areas in terms of size and height. The multi-material design application aims to utilize the vacant square in the northwest corner of the estate and the waste roof space by creating a new vertical tower building with variable space sizes and heights, thereby providing additional communal public spaces and functions for the community. The vertical building design draws inspiration from Adolf Loos's Raumplan concept, which emphasizes spatial hierarchy by organizing interior volumes with varying sizes and heights tailored to specific functional requirements. The newly designed tower building is organized using the sphere packing algorithm to define volumetric spatial units, then through Voronoi algorithm to generate the In-between space enclosure. Figure 10 presents that multi-materials gradation are applied to the space enclosure, resulting in adjustable density, transparency, and color gradation, introducing vibrant space qualities and flexible space organization.

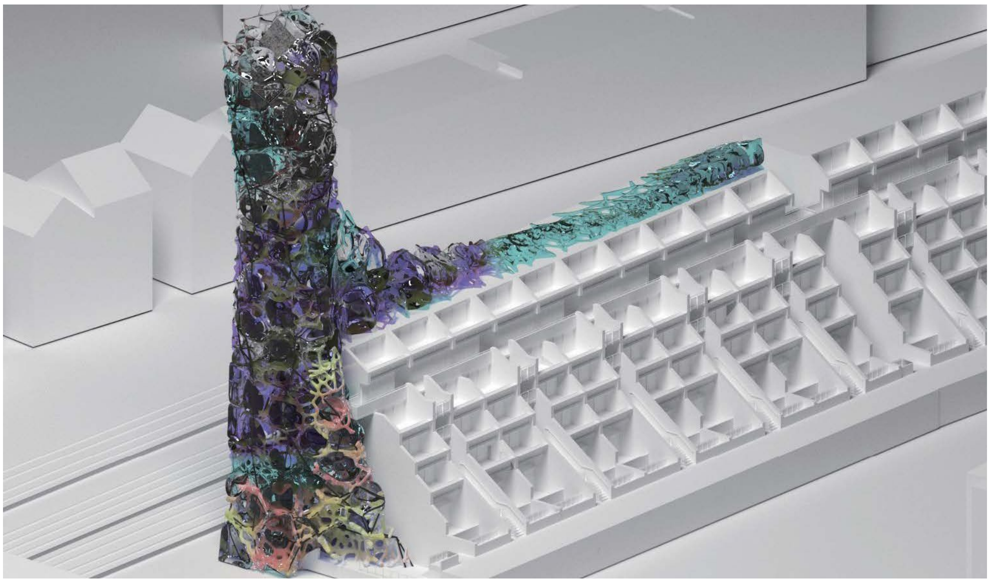

Figure 10. Multi-material gradation applied to the space enclosure, resulting in adjustable density, transparency and color gradation.

4. Discussion

Modernist architecture in London represents a typical residence building style. Many of these buildings have become vacant and are no longer suitable for contemporary residence because of the poor space quality. This research explores a design-based methodology to reclaim vacant space in modernist architure applying recycled plastic multi-material and digital algorithms. Digital algorithms such as circle packing and sphere packing can be applied to define functional spaces which adapt to variable, confined boundaries and environments, allowing flexible adjustment of space size and quantity. The use of recycled plastic multi-material in architecture not only reduces construction costs but also increase resource efficiency, contributing to environmental sustainability. Besides, multi-material has the ability to engage with 3D printing technologies and digital computation to achieve multi-material gradation in thickness, transparency, density, and flexibility, which assists in enhancing space quality based on specific environment requirements. The multi-material design with digital methodology can resolve the key contemporary issues and achieve the evolution of modernist architecture in spatial, social, and material aspects.

Nevertheless, challenges still remain in the application process of plastic multi-material with digital design. Currently, most recycled plastics lack the structural strength required for supporting high-rise buildings independently. Therefore, they must be integrated with conventional load-bearing systems such as steel or concrete frames, requiring careful structural coordination, which need to rely on metal or concrete structural systems and develop effective integrations between plastic enclosures and main structural supports. Another challenge is the fire-catching problem of plastic materials. Further exploration is still required to develop long-lasting fire-resistant coatings for plastics to ensure the safety and durability of structure. Furthermore, the multi-material design with Voronoi algorithm generates the curved enclosure with irregular textures which need to be fabricated by 3D printing technology. The current 3D printing technology can create products of limited size, while technology with printing large scale curved enclosure on real site still requires further exploration.

5. Conclusion

This research analyses the current issues of modernist architecture from space, social, material, and economic aspects. In order to reclaim vacant space and enhance space quality in modernist architecture, recycled multi-material composed of PET and TPU plastic were explored to achieve high performance and used in building construction. The integration of multi-material and digital algorithm such as circle packing, sphere packing, and Voronoi enables to define new functional spaces with adjustable space enclosure. Multi-material gradation on thickness, density, transparency, and flexibility generated by structure, porosity, privacy, and daylight analysis presents the method to create variable space quality based on specific space problems existing in modernist architecture.

The application of multi-material and digital algorithms on real sites such as Stangate House, Alexandra and Ainsworth Estate demonstrates the success of reusing the uninviting vacant space, enhancing space quality and vitilizing the traditional architecture. Overall, recycled multi-material integrated with digital algorithm design methodology has a significant influence on the evolution of modernist architecture, which shows great potential to revitalize and reshape vacant space and historic building in urban city.

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