Modular design and manufacturing processes using space-filling solids.

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This study examines the feasibility of employing space-filling solids in architectural-scale designs and explores the application of digital design methods in digital architecture. Specifically, the comparison and analysis focus on two nature-inspired space-filling solids, namely cubes and truncated octahedrons. The truncated octahedron exhibits favorable flexibility and adaptability when combined with modular design principles. Digital architecture relies on the advancement of digital tools, encompassing digital software and digital machines. Notably, 3D printing possesses exceptional shaping capabilities, offering expanded possibilities for constructing digital architecture.
To investigate digital architectural processes, two experimental case studies are conducted. The first case study involves the design of the 'Flowing apartment,' which employs deformed cubes generated through laser cutting and 3D printing techniques. The second case study features the 'Nomad POD,' designed utilizing deformed truncated octahedrons and 3D printing technology. By utilizing digital design and processing methods, this research contributes to the understanding of digital architectural practices and their connection to digital manufacturing. The integration of space-filling solids, digital design, and 3D printing enables innovative approaches to architectural design and construction. This paper provides insights into the potential applications and benefits of utilizing space-filling solids at an architectural scale, highlighting their role in fostering modularity and facilitating the realization of intricate architectural designs.

Keywords
Space-filling solids, digital architecture, digital design, digital manufacturing, 3D printing.

1. Introduction

The escalating demands of urbanization and population growth have resulted in the scarcity and escalating value of land within megacities. (United Nations Human Settlements Programme , 2020) As the price of land continues to rise, its proportion relative to the total property price increases, necessitating innovative approaches to optimize space utilization in buildings while maintaining affordability. Nature provides a valuable source of inspiration in this regard. To address the challenge of space optimization, the concept of "Mind the gap" (GRIFFITHS, 2012) has emerged, aiming to develop a system that utilizes underutilized areas within cities to expand their capacity. Space-filling solids, such as cubes and truncated octahedrons, offer geometrically suited solutions for filling urban voids, gaps in the urban fabric, and leftover spaces between existing buildings. (Scott, 2011) These solids exhibit structural integrity, enabling their integration into modular design frameworks. By deploying a standardized structure frame, the city's expansion can mimic cellular growth, providing a cohesive structural foundation while facilitating the redefinition of interior and exterior spaces. (Zanni, 2021) The advent of digital design methodologies has opened up new possibilities in architecture, empowering architects with algorithmic, parametric, and nonlinear thinking capabilities, among other advanced tools. (Claypool, 2021) These digital design processes yield visual outcomes that often surpass the limits of imagination. (Bridle, 2023) Furthermore, the seamless integration of digital design with manufacturing processes enhances the potential of digital architecture. (Zixu Liu, 2022) Techniques such as 3D printing, laser cutting, and robotic manufacturing augment production efficiency and accuracy, offering avenues for mass customization. (Berry, 2000) Although the current maturity of these technologies within the architectural field remains limited, their widespread adoption is imminent. (Salvador, 2006)

Vitruvius, an ancient Roman architect, advocated for three fundamental qualities—Venustas (beauty), utilitas (utility/functionality), and firmitas (strength/durability)—in architectural design. (Moragan, 1914) While Vitruvius's principles of beauty have withstood the test of time, the evolution of technology, economics, culture, policy, and population has influenced architects' values and aesthetic perspectives. (Olivier, 2021) Each architectural style, including those stemming from previous industrial revolutions, boasts distinctive characteristics. In the era of the fourth industrial revolution, characterized by digital advancements, architectural designs have embraced a more technological and futuristic outlook through the widespread adoption of digital design and manufacturing technologies. (Fengwei, 2021) Digital technology not only transforms production processes but also shapes aesthetic perceptions. The utilization of digital manufacturing technologies, coupled with the mature use of digital design tools, has spawned a new aesthetic paradigm in digital architecture. (Lin-Lin Chen, 2012) However, it is important to note that the current costs associated with digital manufacturing equipment still exceed those of traditional methods. Nevertheless, the expanding array of options for fabricating non-standard, intricate components offsets these costs. Moreover, with increasing demand, digital mass production in factories can effectively reduce costs while maintaining stringent quality standards. Consequently, the cost differential between a doubly curved façade and a traditional planar wall becomes inconsequential. (Berry, 2000)

This paper endeavors to explore the intersection of space-filling solids, digital design methodologies, and manufacturing processes within the realm of architectural design. By investigating the potential of modular design and digital tools, our research aims to contribute to a comprehensive understanding of the evolving field of digital architecture and its implications for optimizing space utilization in urban environments. (Fbricate, 2011) The integration of computation in architecture began with the advent of computer-aided design (CAD) in the early 1980s, which has now become a standard practice in architectural and engineering offices. In the 1990s, further advancements were made in computer programming and animation software, enabling architects and designers to realize complex architectural design ideas and explore design methods. This period witnessed the emergence of parametric design, algorithmic design, data-driven design, and non-linear design concepts. (Harding, 2012) Parametric design involves expressing design parameters and rules through algorithmic thinking, establishing the relationship between design intent and design response. Parametric modeling software, such as Rhino, Maya, and 3ds Max, enables designers to link models to parameters and modify the shape of the model by adjusting these parameters. (Stavric, 2011) This approach facilitates the rapid exploration of various design schemes, suitable for both irregular and complex shapes in traditional and exploratory design contexts. Many pioneering architects and designers have successfully adopted parametric design methods in their work. Algorithmic design employs algorithm program editors to assist in the design process. (Gursel Dino, 2012) It involves following a set of rules or algorithms, particularly with the aid of computers, to solve design problems. Different scripting languages, such as Rhino script, Python, MEL, and Grasshopper, are utilized within specific design software to manipulate code and generate visual outcomes. Algorithmic design harnesses the computational capabilities of computers, allowing for self-optimization and inspiring designers with unexpected yet controllable results. It is particularly useful for tackling criteria-driven and non-standard design tasks. (António Leitão, 2011)

Parametric design and algorithmic design are distinct approaches, but they often intersect in practice. Designers frequently combine these methods to optimize shapes, alternating between parameter adjustments and algorithmic transformations to achieve the desired design outcomes. Both parameterization and algorithms serve as containers of values, providing designers with the flexibility to adjust code and parameters to achieve different results. Design forms resulting from the combination of parametric and algorithmic design are commonly referred to as Pragmaticism. (Romero, 2021) Computer-aided architecture design (CAAD) encompasses computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies, forming a comprehensive repository of building records employed by architects and architectural companies. The realization of physical entities through CAAD involves three steps. First, designers create 2D or 3D models using digital design software and export them in a format compatible with digital manufacturing software. Next, they process the files using CAM software, configuring parameters for machine operation based on the chosen manufacturing method. Finally, digital manufacturing equipment, such as CNC machines, 3D printers, laser cutters, or robots, is employed to process the materials and fabricate the physical entities. This process seamlessly connects digital design, digital processing, and digital construction, providing precise manufacturing of complex components. Furthermore, the visualization aspect ensures that the digital representation accurately reflects the final physical output. (António Leitão, 2011) (Claypool, 2021)

Effective collaboration between professional designers, construction parties, material suppliers, and subcontractors is crucial for successful projects. Traditional communication methods often fall short in addressing the complexities of modern construction, necessitating digital architecture designers to collaborate with other professionals throughout the design and construction phases. Building Information Modeling (BIM) platforms serve as digital communication hubs for project information. Popular BIM software such as Revit by Autodesk and Digital Project by Gerry Technology, based on the CATIA modeling engine, facilitate collaboration, and allow the importation of digital models from other software. Collaborative design enabled by BIM not only enhances efficiency and convenience but also makes large and complex projects feasible. The continuous collaboration between various teams on the BIM platform brings the project closer to reality, thereby assisting in post-construction activities such as management, operation, and demolition.

2. Materials and Methods.

2.1 Space-filling solids as a design element

Space-filling solids in design explores the concept of utilizing space-filling solids as a design element. The chapter begins by drawing inspiration from nature, where various examples of space-filling patterns can be found. One such example is the hexagonal honeycomb created by bees, which optimizes space utilization without gaps. Darwin's research suggests that bees chose the hexagonal shape because it allows them to store more honey while using less material compared to square or triangular cells. Another natural example is foam, which consists of trapped gas pockets within a liquid or solid structure. Water foams, in particular, demonstrate a flexible and multi-scale system where bubble walls meet at plateau borders. The walls form stable connections, meeting at angles of 120 degrees, and can rapidly rearrange into threefold junctions, when necessary, Additionally, migratory birds offer insight into combining different shapes to reduce wind resistance during flight. The dynamic and flexible connections between individual birds within a migration group result in the creation of various shapes.

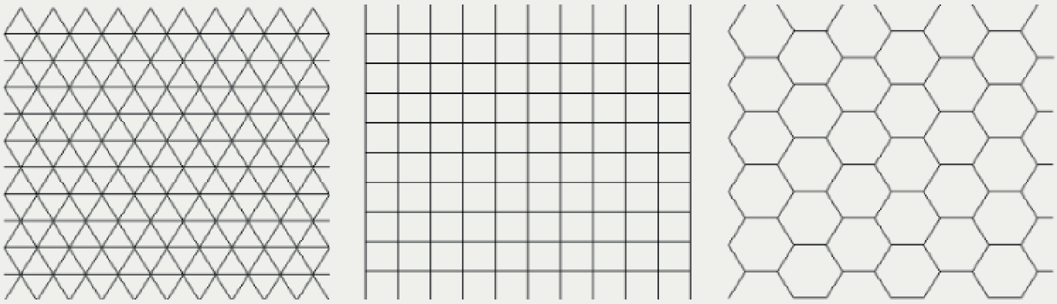


Figure 1. Triangles, Figure 2 Squares, and Figure 3 Hexagons.

Moving into two-dimensional space, tessellation becomes a key consideration for filling a plane with identical, equal-sided, and equal-angled cells. The three options available are triangles, squares, and hexagons (Figures 1, 2, and 3). However, without the constraints of equal-sided and equal-angled cells, an array of geometric shapes can be used to create visually appealing tiles, carpets, and mosaics. Expanding to three-dimensional space, space-filling solids, or space-filling polyhedral, demonstrate elegance in industrial production and architecture. Five primary space-filling convex polyhedra are identified: the cube, triangular prism, hexagonal prism, truncated octahedron, and gyrobifastigium (Figure 4). The cube, with its six square faces, represents the only Platonic solid possessing this property. Other examples include the uniform triangular prism, the hexagonal prism with equal hexagonal bases, and the truncated octahedron with its fourteen faces comprising regular hexagons and squares.

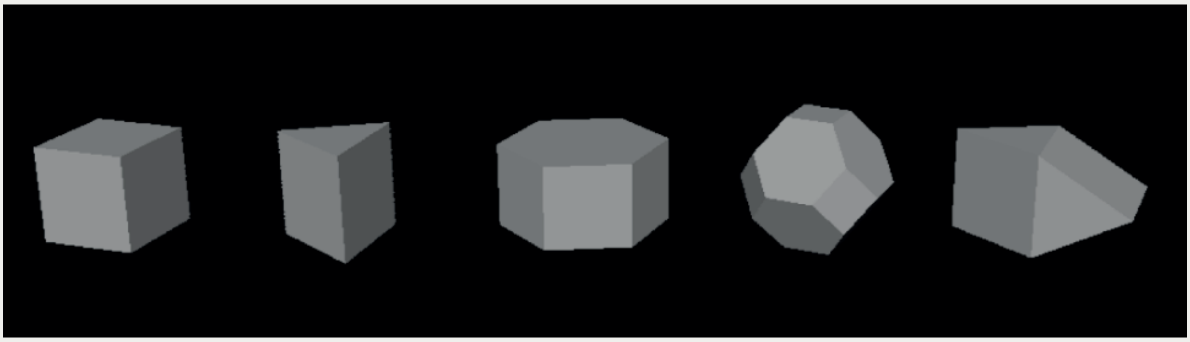
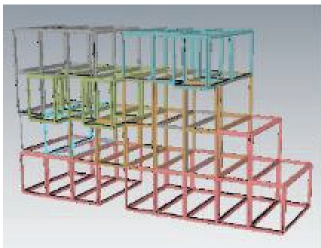


Figure 4. cube, triangular prism, hexagonal prism,
truncated octahedron and gyrobifastigium Source: The Author (2019).

Deforming space-filling solids introduces new possibilities for design. Cuboids, characterized by horizontal floors, vertical walls, and 90-degree corners, offer flexibility in altering space. By adjusting the lengths of the cuboid's edges, the overall space can be transformed while still maintaining its fallibility (Figures 5 and 6). The combination of space-filling solids, such as the hexagonal prism, allows for increased options in spatial organization (Figures 7 and 8). The truncated octahedron, when positioned with a hexagonal face as the base, offers larger horizontal areas and enhances the overall design (Figures 9 and 10). By considering the geometry and employing vertical division, innovative combinations and structures can be achieved while preserving the essence of the original shape.



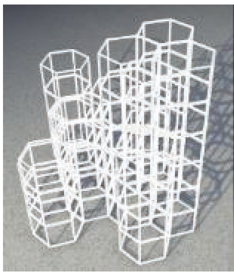
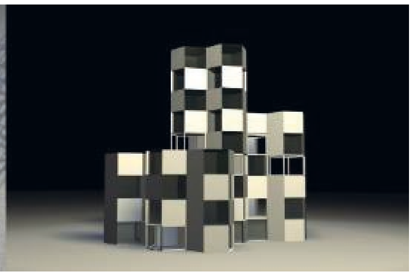
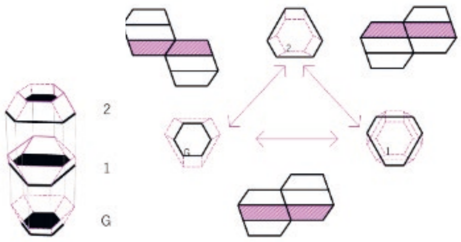



Figure 5. Deformed cube frame structure system.
Figure 6. People eye of a complex building.
Figure 7. Deformed hexagonal prism frame structure system.
Figure 8. people eye of a complex building.



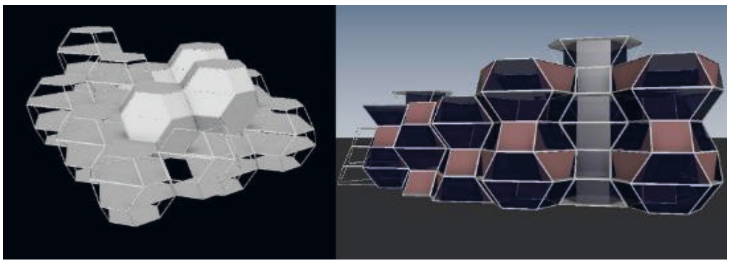


Figure 9. The combination among the three types of floors.
Figure 10. deformed truncated octahedron frame structure system and people eye of a complex building.

2.2 Algorithmic design development.

Table 1. Six loops of a typical group for filling up space.

Loops Directions	Loop 1 (black)	Loop 2 (Green)	Loop 3 (pink)	Loop 4 (blue)	Loop 5 (yellow)	Loop 6 (grey)
X	+0	+4.899	+9.798	+14.697	+19.596	+24.495
Y	+0	+8.485	+0	+8.485	+0	+8.485
Z	+0	+3.464	-3.464	+0	+3.464	-3.464

With the assistance of coding, designers can automate the generation of various combinations using space-filling solids. The Maya Embedded Language (MEL) is a scripting language utilized in Maya, a 3D Graphics Software, to simplify tasks. Although the process is automated, the conceptualization and work still belong to the designer. To enable the truncated octahedron POD to grow automatically, the designer needs to determine the lengths of the three dimensions in the X, Y, and Z directions. After calculating the 3D model, the dimensions are found to be 29.393877, 16.970562, and 10.5, respectively. Combination and repetition play crucial roles in the automation process. While a cube requires a simple loop, the truncated octahedron necessitates six loops (see Table 1 and Figure 11).

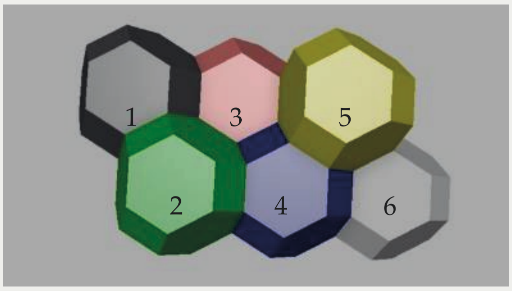


Figure 11. A typical group.

Understanding the aggregation method allows for the completion of over half of the program. Here is an example of one loop within the complete script (As Below) Similar to the above loop, there are five more loops with different parameters. By adjusting these values, diverse architectural forms can be generated (see Figure 12-13). Altering the maximum number of replicates in each direction controls the maximum number of objects generated in each loop. From an architectural perspective, designers can manipulate the size of the site by adjusting the building boundaries and density.

```
float $dx = 4.899; // Define the dimension in the X direction
float $dy = 8.485; // Define the dimension in the Y direction
float $dz = 3.464; // Define the dimension in the Z direction
string $sel [] = `ls -sl`;  // Select an object and store its position

for ($x = 0; $x < 5; $x++) {  // Define the threshold for x
  for ($y = 0; $y < 5; $y++) {  // Define the threshold for y
    for ($z = 0; $z < 5; $z++) {  // Define the threshold for z
      $comp = `duplicate $sel[0]`;  // Duplicate the object
     move -r ($x * 29.393877) ($y * 16.970562) ($z * 10.5) $comp;  // Move the duplicated object to the specified location
      refresh;
    }
  }
}
```

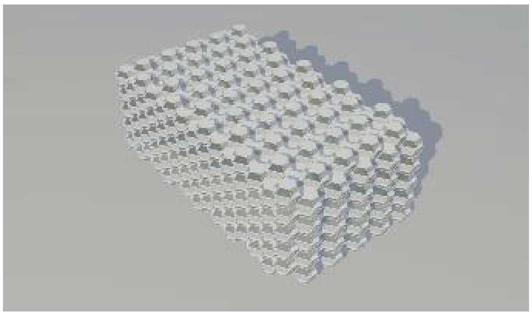


Figure 12.
Bird eye of a box shape building.

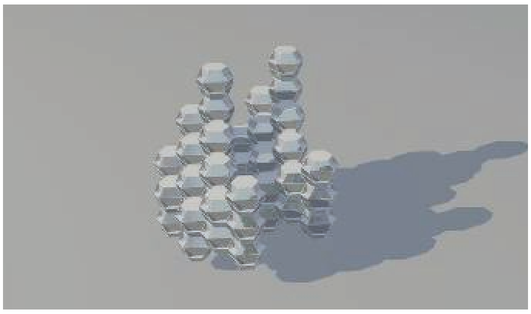


Figure 13.
Bird eye of a multi-story building.

Architecture driven by data is an emerging approach to design. In today's digital world, our online activities and information are continuously collected. Platforms like Google Trends analyze vast amounts of user search data to identify various trends (see Figure 14). For instance, it reveals that people prefer renting studios over one-bedroom or two-bedroom flats, with less demand for the latter. Such data-driven insights can inform the design of residential buildings and cater to the demand for different types of housing. As we gather data from natural sources (such as sun, wind, water) and artificial sources (such as commercial buildings, residential buildings, roads, stations, bridges), we can establish different parameters and constraints. Building regulations can also be considered as guiding data for automated design. In this exercise, random data is used to represent unknown constraints, providing an intriguing demonstration of data-driven architecture design. A random number is employed as a condition for duplicating the truncated octahedron POD. If the conditions are met, the POD is duplicated and moved to a specified location. The following is the core loop of the entire script:

```
float $dx = 4.899;  // Define the dimension in the X direction
float $dy = 8.485;  // Define the dimension in the Y direction
float $dz = 3.464;  // Define the dimension in the Z direction
int $amount = 2;    // Set an integer
int $max1 = 2;      // Set an integer
int $max2 = 2;      // Set an integer
int $max3 = 12;     // Set an integer
string $sel[] = `ls -sl`;  // Select an object and store its position

for ($x = 0; $x < $max1; $x++) {    // Define the threshold for x
  for ($y = 0; $y < $max2; $y++) {  // Define the threshold for y
    for ($z = 0; $z < $max3; $z++) {  // Define the threshold for z
      int $rand = rand($x + $y + $z);  // Define the threshold for the random number
      if ($rand % $amount == 1) {  // Set a condition for the random number
        $comp = `duplicate $sel[0]`;  // Duplicate the object if the random number meets the condition
          move -r ($x * 29.393877) ($y * 16.970562) ($z * 10.5) $comp;  // Move the duplicated object to the specified location
        refresh;
      }
      else {  // Do not duplicate the object if the random number does not meet the condition
        continue;
      }
}
```

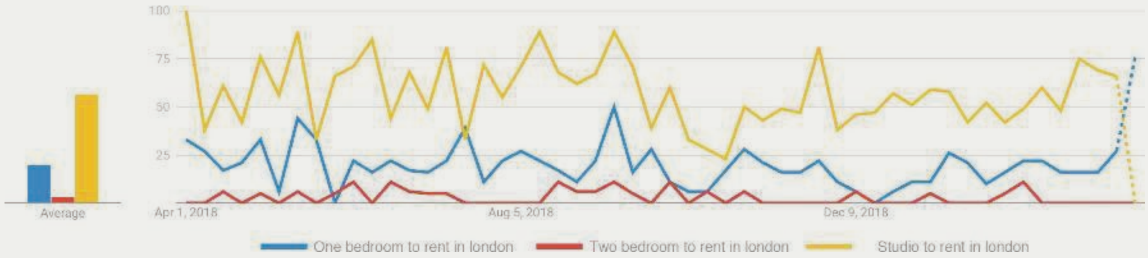


Figure 14.
The trend of rental demand of different types of houses in London.

By adjusting the values of the variables, different architectural forms can be generated. For example, setting the value of `$amount` as 4, `$max1` as 3, `$max2` as 3, `$max3` as 8, and using `$rand` as`rand ($x - $y + $z) `, an irregular pattern combination is obtained (see Figure 15). Varying these parameters and conditions yields different designs, such as a deformed tower with overhanging PODs (see Figure 15), a residential area comprising multi-story complexes (see Figure 15), or a combination of two small towers (see Figure 15). Although these designs may appear unconventional due to the random data used, they showcase the intriguing possibilities of data-driven architecture. As restrictions can be quantified and defined with suitable parameters, the results become more informative and practical. Furthermore, the integration of artificial intelligence and machine learning in design processes holds great potential. The application of digital design is still evolving, and with technological advancements, AI-driven design is expected to become a significant trend in the future.

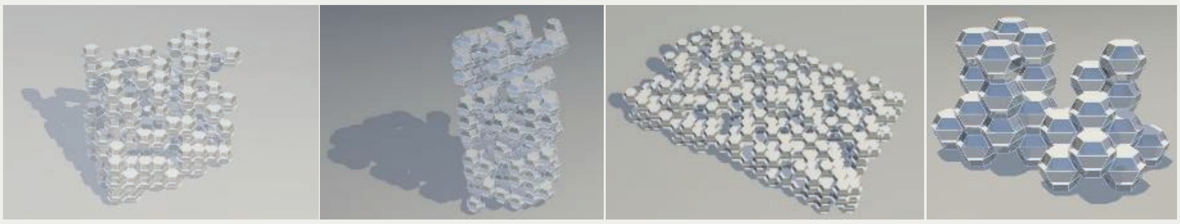


Figure 15.
Bird eye of an irregular building, bird eye of a deformed tower,
bird eye of a residential area, bird eye of a two-tower building.

2.3 Free design tool for POD design

There is a wide range of digital design methods available in architecture, each suited to different conceptual requirements. When considering the concept of the "Nomad POD," it becomes evident that buildings need to adapt to the various life stages of their occupants. Different life stages entail different demands for living spaces. In alignment with the standard POD, which is based on a deformed truncated octahedral shape, several variations of PODs have been designed to serve different functions. The frame structure POD serves as the foundational element, providing structural integrity. By adding a slab onto the frame, shared facilities, open spaces, or green areas can be created. Further additions of walls and roofs result in inhabitable spaces. These different POD configurations, including the frame POD, panel POD, and six room module PODs, offer discrete combinations to cater to specific stages of human life. (Figure 16)

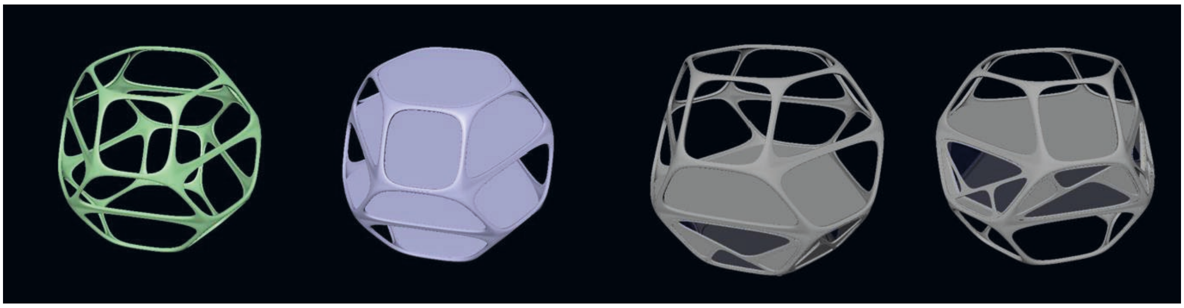


Figure 16.
Frame POD, panel POD, room module PODs

Through the use of architectural terminology and design principles, the Nomad POD concept demonstrates the versatility and adaptability of buildings to meet the evolving needs of their occupants. The variations in POD configurations provide opportunities for flexible and functional spatial arrangements, allowing for efficient use of space and the optimization of living environments.

3. Results

3.1 Prototyping through digital fabrication

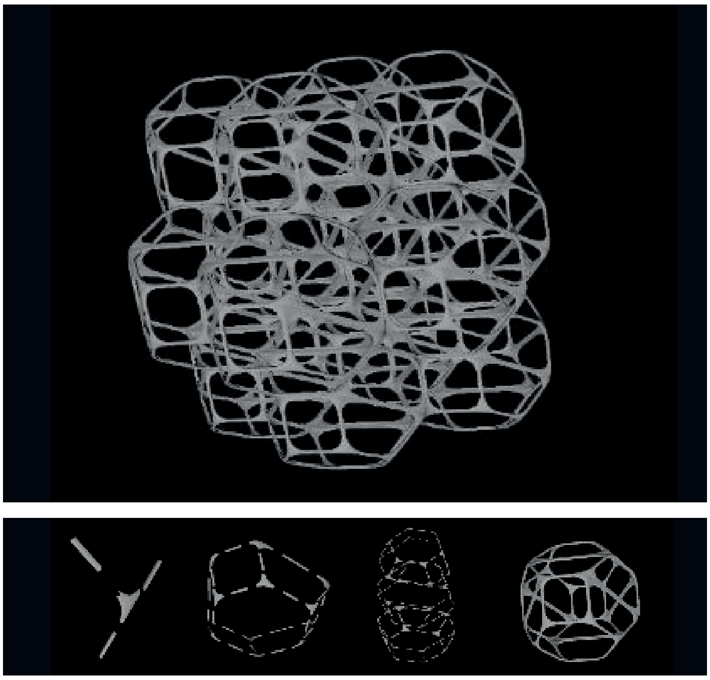


Figure 17.
Frame structure system and non-standard joints and beams.

Digital manufacturing, including the use of 3D printing technology, has gained significant traction as a versatile and efficient method of construction. By leveraging digital design and computer-aided manufacturing (CAM), digital manufacturing processes have become more streamlined and effective. While off-site manufacturing remains prevalent, allowing for modular component production in factories and subsequent on-site assembly, there are also on-site digital manufacturing applications for smaller-scale buildings. The distinct advantage of 3D printing lies in its ability to shape complex, three-dimensional forms with precision. Unlike traditional construction methods that often rely on fitting irregular components using standardized elements, 3D printing enables direct fabrication without the need for alterations. This ensures that the final product closely aligns with the original design, preserving the aesthetic integrity of the architectural space. In the case of the "Nomad POD" concept, the frame structure system assumes a crucial role. (Figure 17) illustrates non-standard beam and joint components that present challenges when employing traditional construction techniques. However, 3D printing offers a solution by maintaining design accuracy without compromising architectural aesthetics. The outer layer, composed of fireproof plastic, is 3D printed, while the inner layer consists of reinforced concrete. The 3D printed plastic serves as a mold for the concrete, eliminating the need for additional decorative finishes. This approach allows for customization, enabling the printing of varying plastic thicknesses to meet insulation specifications and incorporating insulation material between double-shell plastic layers. Such optimization reduces material waste and ensures the distribution of structural forces in an efficient and dynamic manner.

While large-scale on-site 3D printing of concrete is being explored, limitations in printer size and working radius often necessitate off-site component manufacturing and subsequent on-site assembly. Two methods can be employed: pre-casting plastic and concrete components off-site and assembling them on-site, or printing plastic off-site, assembling plastic molds on-site, and pouring concrete into hese molds. Each approach offers advantages, such as increased production control and reduced transportation costs. To showcase the potential of 3D printing in digital manufacturing, two models were created using standard FDM 3D printing: a 1:20 scale representation of a standard frame POD and a 1:2 scale component model. These models demonstrate the feasibility and effectiveness of 3D printing for architectural applications, highlighting its role in enhancing the construction process.

3.1.1 3D printing 1:20 scale model (prototyping)

The frame POD, as a typical example, consists of various components, including four types of joints and seven types of beams, totaling 66 parts (Table 2). Given the 1:20 scale of the model, the components are relatively small and do not contain concrete fillings. In practice, steel joints are incorporated into the components for convenient assembly. A 2mm diameter steel bar is employed as the connecting element (Figure 19). To streamline the assembly process, each component is marked with unique identifiers during production, facilitating efficient and accurate assembly (Figure 18).

The assembled 1:20 model, divided into three floors, demonstrates the flexibility of the design (Figure 19). Through digital manufacturing techniques, the transition from digital design to production is expedited, increasing the likelihood of transforming design concepts into tangible structures. The modular production in factories has benefited from enhanced precision and quality. The 3D printer, as a pivotal digital manufacturing tool, can either print the entire object in one go or fabricate modular parts for subsequent assembly. In either case, the overall structure's shape remains intact and unaffected. The utilization of digital manufacturing equipment not only saves time but also improves the feasibility of materializing architectural designs. Factory-based modular production ensures high precision, while 3D printing enables the creation of intricate components with ease. By bridging the gap between digital design and physical construction, digital manufacturing presents a powerful avenue for realizing architectural visions.

Table 2.
Components of the basic frame POD.

	Types	Position	Numbers	Memo
1			6	joint
2			6	joint
3			6	joint
4			6	joint
5			6	beam
6			6	beam
7			6	beam
8			6	beam
9			6	beam
10			6	beam
11			6	beam

Figure 18.
Parts of the joins and beams.

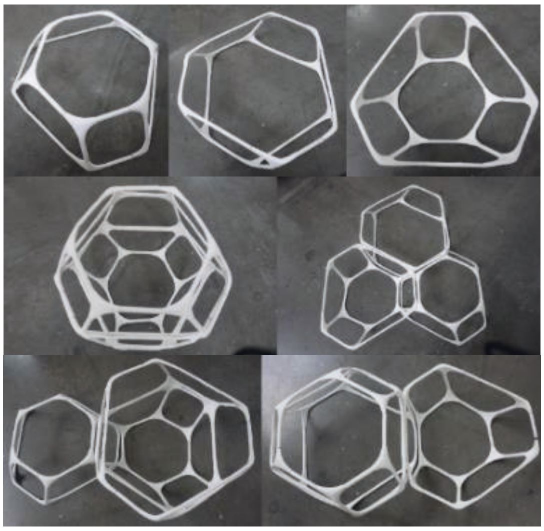


Figure 19.
Assembled 1:20 model divided into three floors, and combinations of the three floors.

3.1.2 3D printing 1:2 scale model with precast concrete

Due to time and budget limitations, a portion of one joint from the overall frame POD was selected for the 1:2 scale model (Figure 20). The dimensions of this model are 92mm, 127mm, and 237mm, respectively. The Ultimaker-3 printer was utilized for this project, which offers printable dimensions of 197mm, 215mm, and 200mm (Ultimaker-3 website). Since the component exceeded the printer's size capacity, it was divided into four parts using Luban software, a CAM tool that automatically subdivides large components and generates connectors (Figure 20).

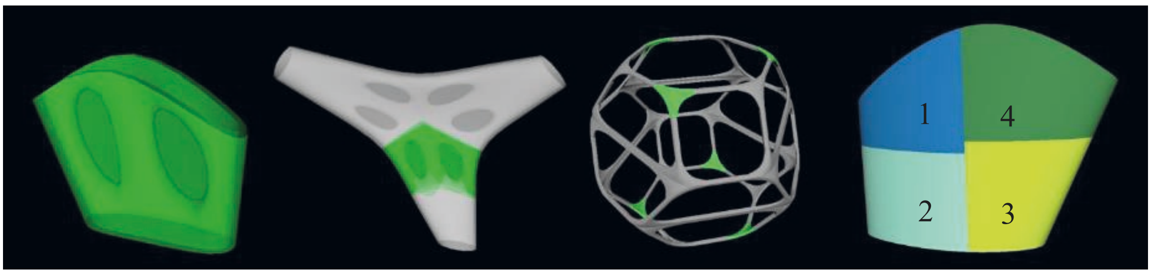
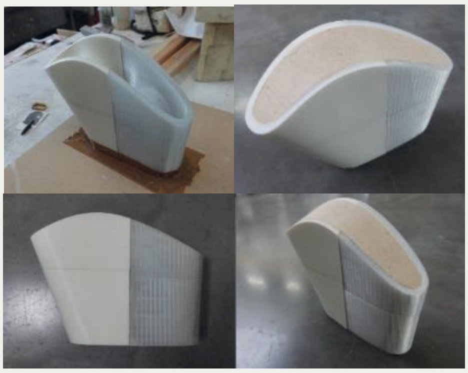


Figure 20.
X-view of 1:20 scale digital model and the location on the frame structure and component divided by 4 parts.

After completing the digital model, the file was imported into Ultimaker Cura software to set the 3D printing parameters, such as print speed, temperature, and layer height. This step allowed for model inspection, identification of any issues, and estimation of printing time and material requirements (Table 3). Instead of fireproof plastic, white PLA, and transparent PLA with a diameter of 2.85mm were used for the experimental printing.

Table 3.
Information table for each component.

Component	Time	Material weight	Material length
Part 1	14h 37min	221g	28m
Part 2	13h 29min	201g	26m
Part 3	13h 52min	213g	27m
Part 4	14h 41min	225g	29m
Total	56h 39min	860g	110m



During the printing process, the support materials were also printed layer by layer to ensure structural stability (Figure 21). The four printed parts were subsequently assembled (Figure 21, 22). While the entire building is supported by reinforced concrete, the plastic shell serves to shape the continuous surface and contribute to the building's aesthetic appeal. In this case, the internal shape of the component was redesigned to align with the distribution of forces, allowing for material savings, ease of transportation, and installation. Concrete was poured into the plastic mold to complete the component (Figure 22). The combination of digital manufacturing techniques and concrete pouring enables the realization of complex architectural designs with enhanced efficiency and accuracy.

Figure 21. Sections and final digital models, Part 1, and Part 2 in printing.
Figure 22. Plastic shell preparing for pouring concrete. And part 1, 2, 3, 4 of the scale 1:2 model.

4. Discussion

The discussion surrounding digital design and manufacturing in architecture highlights both the immense possibilities and the current challenges in this field. The "Nomad POD" project serves as a prime example, showcasing the flexibility and creative potential of digital design, particularly through the utilization of space-filling solids. The integration of big data analysis further enhances the scientific and intelligent aspects of architectural design. However, it is crucial to acknowledge that digital design is still a nascent discipline, and there is much room for growth and development. Digital manufacturing, a vital component of this process, brings automation and efficiency to construction practices. 3D printing technology, in particular, offers the advantage of producing intricate and precise shapes without relying on traditional fitting techniques. Yet, challenges arise when translating these advancements to real-scale construction. Limitations such as the size of 3D printers, structural stability, and material strength present obstacles that need to be addressed for widespread implementation. Presently, 3D printing is primarily employed for constructing wall components, while other architectural elements still rely on conventional construction methods. However, modular 3D printing conducted off-site emerges as a promising solution. This approach enables the fabrication of complex non-standard components and addresses the construction of large irregular surfaces. By combining the precision of digital manufacturing with the efficiency of modular construction, this method has the potential to revolutionize the architectural industry. In conclusion, digital design and manufacturing have opened up new horizons for architectural exploration. While substantial progress has been made, ongoing advancements and innovative solutions are necessary to overcome existing challenges. By embracing these opportunities and pushing the boundaries of technology, the integration of digital design and manufacturing can reshape the future of architecture, offering groundbreaking possibilities for construction practices.

5. Conclusions

In conclusion, this research has explored the implications of digital design and digital manufacturing in the field of architecture. The study has demonstrated that a variety of digital design methods can generate multiple outcomes in a short timeframe, leveraging the design potential of computers and offering new avenues of inspiration. Algorithmic design, artificial intelligence, and big data analysis have emerged as prominent trends, shaping the future of digital design. Space-filling solids have been identified as a significant element in digital design, facilitating architectural diversity and enabling the exploration of modular architecture solutions. The use of deformed geometries derived from these solids presents opportunities for innovative room configurations. Furthermore, 3D printing technology has revolutionized digital manufacturing by allowing the production of non-standard complex shapes through the printing of modular components. This advancement has eliminated the need for traditional fitting techniques, enhancing efficiency and precision in the manufacturing process. Through the analysis of two experimental case studies, the research has provided a comprehensive overview of the digital design, processing, and manufacturing procedures. The findings highlight the flexibility, efficiency, and seamless integration of these processes. While digital design and manufacturing offer immense potential, it is important to acknowledge that the subjective nature of aesthetics and the complexity of architectural design continue to require human expertise and intervention. This research contributes to the academic discourse on digital design and manufacturing in architecture, providing insights and references for further exploration and development in this field.

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