SHAPE-SHIFTING ARCHITECTURE - AN APPROACH TOWARDS SUSTAINABILITY

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ABSTRACT

In a world, where going sustainable became imperative, new approaches emerge every day in many disciplines to achieve it. The uprising approaches are usually a result of technological innovations and cultural/human factors. While their success and continuity depend greatly on the economic factor. Recently, experts called for a more dynamic architecture that adapts to users and environment, not only users adapting with, like in static architecture. As a result, shape-shifting architecture emerged. Hence, the study aims at investigating it and its role in enhancing and promoting sustainability, particularly in developing nations. The research discussion and findings provided a fulfilling overview of this trend. The study, which was substantiated by numerous case studies, classified shape-shifting architecture into two possible categories and four types. It was discovered that 4D (Dimension) printing can act as a great tool in developing two of its types; which are connected to shape-shifting materials. Finally, the results indicated that this architecture might encounter numerous issues if it were to be scaled up and implemented in developing nations.

Keywords: Shapeshifting Architecture, 4D Printing, Sustainability, Adaptive Architecture

1. INTRODUCTION

Specialists always dreamed about creating buildings that can change in response to the environment and climate, react to their users' ever-changing emotions and needs, and develop, grow, and evolve just like living organisms do Coyne (2016). Some even began to question whether building structures can change shape, morph, and carry out their intended functions in different forms and shapes. Luckily, as noted by David Ben-Grunberg and Daniel Woolfson, buildings that can adapt and alter their shapes also represent a much more sustainable way of life Lieff (2017). Consequently, shape-shifting architecture, one of the latest trends, appeared in response to this vision. And in this era, it is believed to be no longer a far-fetched idea Ned (2019).

Putting in mind that in responsive architecture, shape-shifting refers to more than just physically moving inhabitants. However, the majority of modern architecture is static. Thus, it became a new goal to create architecture that is becoming less static and more dynamic with the aid of technological advances. The purpose of technology in such designs is to assist specialists in achieving a higher state of consciousness and increasing their level of self-awareness, making the impossible possible Lehman (2017). Thus, architects and engineers who think creatively can produce designs and buildings that are able to change their shape as though by magic Lieff (2017).

When researching shape-shifting architecture, it was discovered that it was also referred to as dynamic, responsive, or adaptive architecture. Designer Maria Lorena Lehman, the winner of the Harvard University Digital Design Prize for the most inventive use of digital media in relation to the design professions award and one of the foremost experts on creating great user experiences through smart building design was one of many who used the terminology shape-shifting architecture. She even proposed seven ways to give shape-shifting architecture meaning from a user-centered perspective. They are shape-shifting due to; users' emotions or behavior; weather patterns; social media if architecture is at an event; users' functional requirements; changing contextual urban surroundings; time as perceived by users; and finally shape changed by virtual reality from an off-site environment Lehman, (2023). Furthermore, it was found that various ideas and methodologies started to evolve to develop shape-shifting architecture. For example, North Carolina State University (NCSU) researchers have created materials that can be used to build structures that may change into a variety of several architectural designs. They aim to apply those materials in anything from robotics to construction. The kirigami units they developed, illustrated in Figure 1, are connected as part of the metamorphosis system. In other words, the items cannot be disconnected once they are connected to one another. However, the larger structures they produce can change into numerous, distinct architectures Shipman (2021).

Figure 1

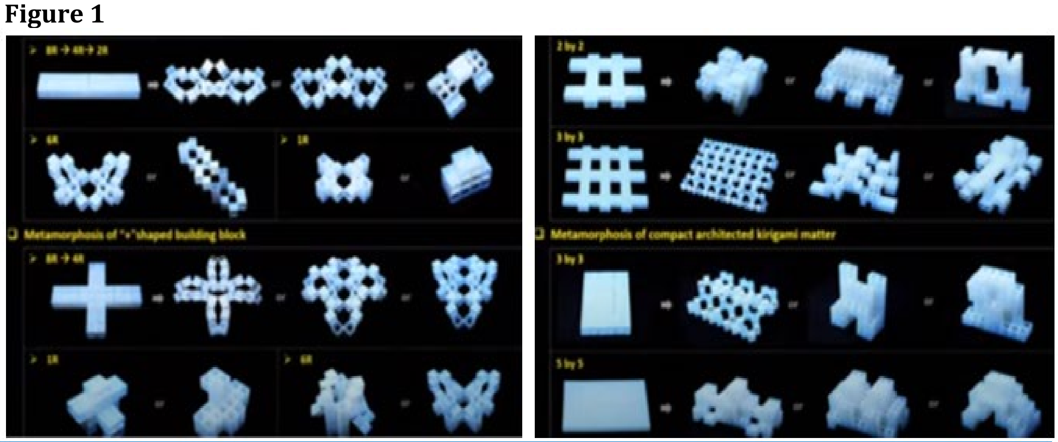


Figure 1 (a) & (b) The Kirigami Units Developed by NCSU Researchers **Shipman (2021)**

Another approach, to achieving this architecture, was presented in a residence in India. It was designed by Matharoo Associates. Its main idea is when pressing a button, the massive marble walls became rotating and sliding panels as demonstrated in Figure 2 Some walls include panels that move back and forth, while others have two levels of panels that rotate in opposite directions Golenda (2017).

Figure 2

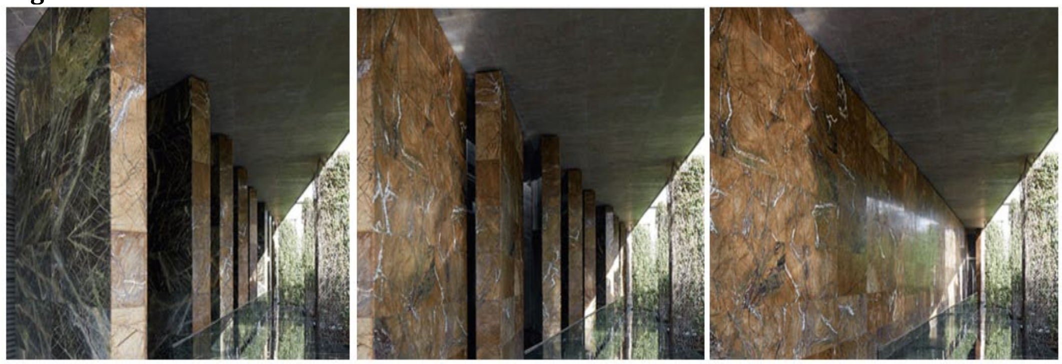


Figure 2 (a), (b), & (c) A home Shifts its Shape by Using Rotating and Sliding Walls **Golenda (2017)**.

Another example was a dynamic shape-shifting helix bridge that was the winner in many contests. The bridge's shape changes when people pass through it, as seen from its design illustrated in Figure 3. This bridge would be an interesting place to walk across because it was suspended quite high above the ground and tucked between two buildings Lehman, (2023). The design also considered many sustainable factors such as using photovoltaic energy, air-cleaning plants, and LED RGB technology as shown in Figure 4 and Figure 5 Arquitectura (2011).

Figure 3

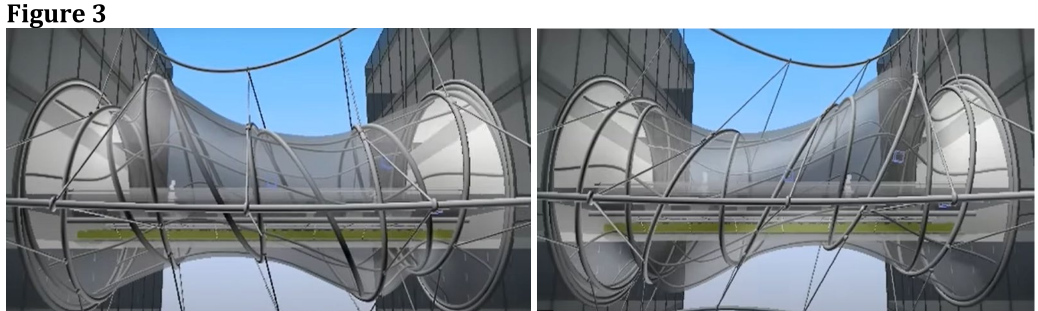


Figure 3 (a) & (b) The Dynamic Shape-Shifting Movement of Helix Bridge Arquitectura (2011).

Figure 4

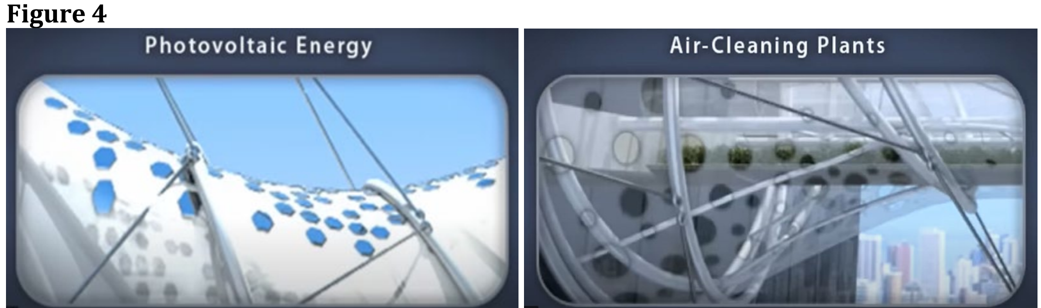


Figure 4 (a) The Photovoltaic Energy and (b) the Air-Cleaning Plants Used in the Bridge **Arquitectura, S. (2011)**.

Figure 5

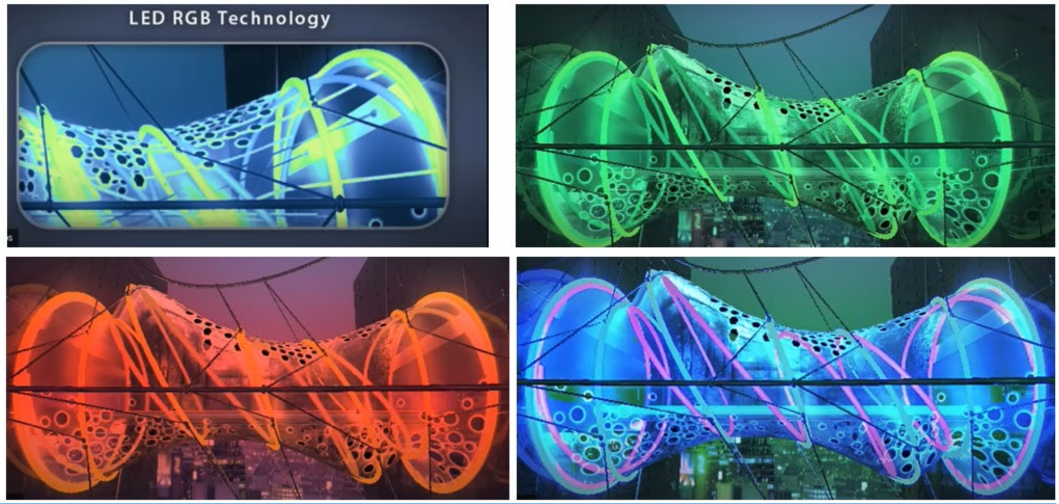


Figure 5 (a), (b), (c) & (d) The LED RGB Technology Used in the Bridge **Arquitectura, S. (2011)**.

Even the students at the Institute for Advanced Architecture of Catalunya in Barcelona were interested in learning how physical spaces might change in the future depending on numerous environmental factors. As a result, geometries with a composite material made of shape memory polymers were created. When activated by stimuli like heat, humidity, and light, created geometries can deform and then return to their original configuration Building Design and Construction (2014). This approach aroused the question about the relationship between shape-shifting architecture and 4D printing. It was found that the concept of 4D printing first emerged in 2013, in the same period of shape-shifting architecture, and research into it has drawn unsurpassed interest. Where it aids in creating dynamic constructions with customizable material properties, functionality, or shapes. This capability primarily depends on a suitable assembly of intelligent materials in three dimensions. While the distribution of various materials in the structure requires mathematical modeling Momeni et al. (2017) . Many examples were found for the use of 4D printing, for example, at Harvard's Wyss Institute for Biologically Inspired Engineering, a team of researchers has been formed to make a new material called hydrogel. The material takes its cue from flowers, which adapt to their surroundings by changing their shape. It is made of wood-derived cellulose fibrils. Their function is to simulate the microstructures of flowers, which allow flowers to change shape. The hydrogel can thus mimic flowers' ability to change their structural composition in response to changes in temperature, humidity, etc. Additionally, the first-ever 4D-printed water valve was created by an Australian research team at the University of Wollongong. The valve automatically closes when hot water is applied to it and widens when the temperature drops, which is a tremendous accomplishment. This phenomenon is made feasible by the hydrogel ink used in 3D printing, which reacts quickly to high temperatures Sculpteo. (2023). Thus, it seems that due to this potential for creating materials that may change shape in response to stimuli, 4D printing has been linked to shape-shifting architecture, which will be further discussed and validated.

As a result, the purpose of this study is to provide answers to some queries about the significance and meaning of shape-shifting architecture and how it relates to 4D printing. This has been investigated to determine its worth in enhancing sustainability. Finally, the study will attempt to analyze the potential for applying this architecture, particularly in developing countries such as Egypt. Since some object to it being still mostly just interesting conceptual projects without actually being constructed to evaluate it. Its potential for use in architecture is called into question. According to Shambayati, it depends on how one defines architecture. In his opinion maybe a whole apartment building won't be shape-shifting soon, but something such as a pavilion can be easily achieved Stinson (2014).

2. METHODOLOGY

The goal of this work is to comprehend the shape-shifting architecture trend and its contribution towards enhancing sustainability. It also seeks to analyze its ability to be used in developing countries. First of all, a lot of the available information and case studies linked to shape-shifting architecture were reviewed. Where the introduction gave a preview of shape-shifting architecture while discussing past research and works with the help of some examples and applications. From this literature review, a question about the relationship between shape-shifting architecture and 4D printing rose.

Therefore, by analyzing all acquired information, the next part strived to establish a clear definition to what is shape-shifting architecture, its aims, advantages, and disadvantages while providing two case studies to represent and demonstrate its application. That was followed by illustrating the meaning of 4D printing through discussing its definition, process, and advantages while demonstrating some examples. From that, the study was able to identify the relationship between the two. Then an analysis of the possible categories and types of shape-shifting architecture supported by multiple case studies was provided. Both the findings and discussions allowed for a clear view and understanding of the trend; and how it contributed to sustainability has been deduced, especially from developing countries' points of view as aimed by the study.

3. FINDINGS

3.1. SHAPE-SHIFTING ARCHITECTURE

Currently, the architecture field is changing, and shape-shifting architecture is one example Garani et al. (2020). It was discovered that the word "shape-shifting" dates back to around ten to eleven years. It is sometimes referred to as an adaptive sensory environment Lehman (2017) or responsive architecture, etc. Garani et al. (2020). This is because by incorporating computing power into architectural spaces and structures and using sensors or control systems to monitor, adapt, and react to actual environmental conditions, buildings can alter their shape, form, or even location Garani et al. (2020). Thus, this type of architecture usually acts as a conduit between data and users, assisting users in interpreting, analyzing, and even reacting to incoming information Lehman (2017).

Definition

According to the Cambridge Dictionary, shape-shifting means the capacity for an imaginative being or thing to transform into another form or shape Cambridge Dictionary (2023). Thus, shape-shifting architecture can simultaneously be defined as the ability of buildings to transform their forms into other forms. This can happen due to a certain stimulus Building Design and Construction (2014) or need

Golenda (2017), coming from the environment, climate, or users Coyne (2016). Thus, it will deal with architecture, users, and environmental data Lehman (2017). The morphing and transformation can be achieved on the scale of the building as a whole Sanzpont (2011) or on an element scale Golenda (2017), using structures Lieff (2017) or materials Building Design and Construction (2014) as their tools.

Aims, Advantages and Disadvantages

A morphing or shape-shifting architecture, according to Maria Lorena Lehman, can react to almost anything. This makes its changeability relevant to its location, context, and users Lehman (2023). That is why, its main aim is to be more responsive to its environment's elements Garani et al. (2020). , functions, users Lehman, (2023), etc. While its designed buildings, with their moving walls, rotating rooms, or sliding surfaces, will enable buildings to optimize occupant comfort by automatically adjusting to changes in light Garani et al. (2020) , temperature Stinson (2014), humidity Coyne (2016) wind, rain, and other environmental factors Garani et al. (2020). Additionally, these buildings have smart technology, systems, elements, and/or materials that successfully provide customizability by sometimes including large, building-scale kinetic elements Golenda (2017). This gives this architecture the advantage of being more flexible and adaptable Stinson (2014) while becoming unique and sustainable. Another aim, and also advantage, is to achieve a balance between the forms and users, by moving the architecture forms along with the users and helping them with decision-making Lehman (2017).

And like any other adaptive architecture, at instances shape-shifting architecture may need to query its users since it strives to have better communication with them. Where the way a geometric form is interpreted and used might greatly depend on how quickly it changes physically. Thus, the time factor was included and shape-shifting may need to occur quickly in order to present the ideal design solution for an immediate user need Lehman (2017). And to better achieve the aimed goals, architects must first ask themselves "why", when deciding which shapeshifting technique and type to employ. This is to get to the heart of the meaning and purpose of the design and develop original ideas Lehman, (2023). All of this allows shape-shifting architecture to surpass the boundaries of the physical domain. Where it will affect the five levels of human experience; physiological, intellectual, behavioral, emotional, and spiritual with the dynamic changes in its space. For instance, as physical changes occur in architecture, emotional changes in occupants may also occur Lehman (2017).

Finally, as it is essential to comprehend the advantages of modern architecture, shape-shifting included, it is also important to understand its disadvantages Lehman (2017). When analyzing its applications some disadvantages were observed. For instance, some of the most avant-garde designs remain in the conceptual stage Lieff (2017). Also, it requires a high level of technology and innovation whether in structures or materials that maintains it in the domain of experimenting and prevents it from scaling up. Furthermore, its construction, operation, and maintenance costs could surpass any reductions due to savings in energy and electricity.

Application (1): Sharifa-Ha House

One of the most commonly used examples in association with shape-shifting architecture is the Sharifa-Ha House in Tehran Lieff (2017), which was completed in 2013 Hohenadel (2014). This home was designed by Tehran-based firm NextOffice Golenda (2017) and its construction was constrained by its limited urban footprint Lieff (2017). It was created to adjust to Iran's changing climate by opening up rooms Golenda (2017) and patios in the summer Garani et al. (2020) and closing them up in the winter Golenda (2017) to keep the house warm Lieff (2017). The architect achieved that by creating three swiveling pods Golenda (2017) or chambers that are nearly horizontal Lieff (2017) and may be turned 90 degrees as illustrated in Figure 6 Golenda (2017). Thus, when summertime comes, three of the house's rooms, or pods can rotate 90° outward opening up terraces to allow each room to have access to the terraces and views above as shown in Figure 7 Lieff (2017). Then it rotates back to a horizontal position to maintain heat in the house during the chilly winter Lieff (2017) by offering minimal openings Hohenadel (2014) .

Figure 6

Figure 6 (a), (b), (c), & (d) The Sharifa-Ha House in Tehran, the Pod House **Lieff (2017)**.

This is why the Sharifi-ha house in Tehran, which shifts with the seasons Lieff (2017) to adapt to Iran's fluctuating weather Garani et al. (2020), is considered one of the applications representing shape-shifting architecture. Where its architect designed it to act as a living organism, changing according to the changes of its environment Bignali (2016). To be able to create this dynamic façade, architect Alireza Taghaboni used foldable balustrades that may tilt up or down as the pods turn Lieff (2017). The turning mechanism used is similar to the method used in turning car-shows floor exhibitions and theater sets Hohenadel (2014).

Figure 7

Figure 7 (a) & (b) The Rotating Process and Room Functions in Sharifa-Ha House Hohenadel (2014) & **Archdaily (2014)**.

Architect Taghaboni when designing this house took its inspiration from Iranian traditional houses Bignali (2016). The building is 1400 m² Bignali (2016) and its structure is built around a central void that permits light to penetrate through the home's floors, while the rooms are facing inward as illustrated in Figure 8 and Figure 9 Hohenadel (2014). The three revolving rooms were designed as a breakfast room, a guest room, and a home office on the first, second, and third floors. However, the designers claimed that the rooms' functions are resilient and could be modified to suit the needs of the residents Hohenadel (2014). For instance, the guest room, which is on the second level, might be set out differently depending on whether or not there is a guest Archdaily (2014). Additionally, numerous studies were used to create the ventilation system. Finally, thanks to digital simulations of various systems, the studio has thoroughly examined static/dynamic performances as well Bignali (2016).

Figure 8

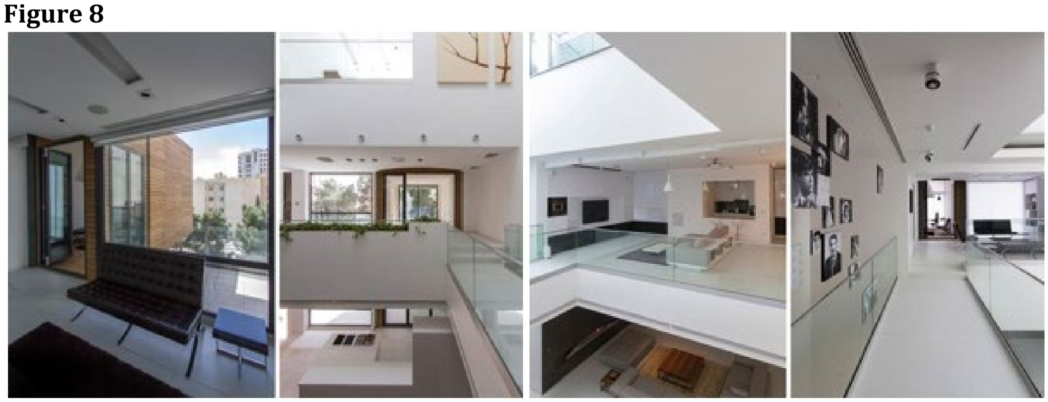


Figure 8 (a), (b), (c), & (d) Various Interior Shoots for the Sharifa-Ha House Demonstrating the Central Void and Light Access Through It **Bignali (2016)**.

Figure 9

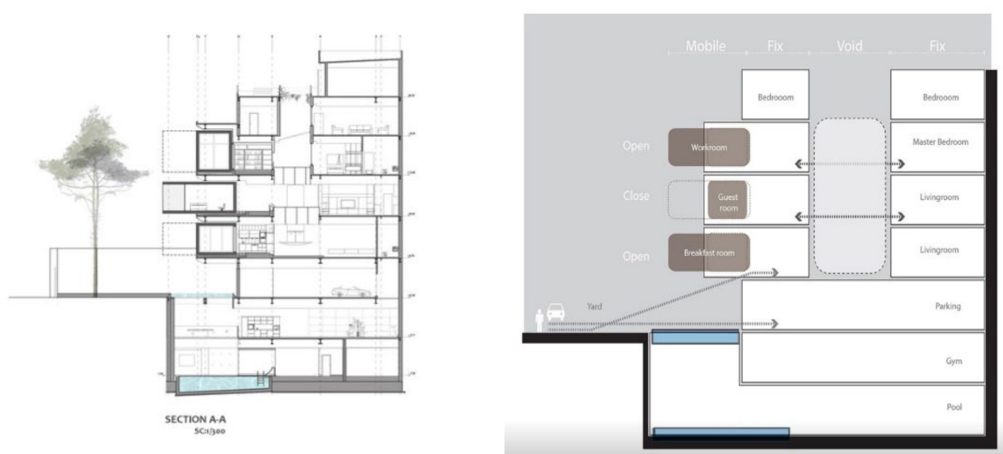


Figure 9 (a) & (b) Sections Showing the Seven Floors and the Central Void **Archdaily (2014)**.

Application (2): The Motus House

Another example of shape-shifting architecture is Motus House which is demonstrated in Figure 10 Geere (2015). Todd Fix, an architect, collaborated with engineers from all fields to develop a proposal for a magnificent zero-energy home that, from an aesthetic standpoint, is unlike anything else Abendroth (2017). Its uniqueness comes from designing it without following the traditional passive design guidelines Geere (2015). Depending on the design of the created proposal, the floor size can range from 5,000 to 12,000 square feet Geere (2015). This cutting-edge home Grozdanic (2015) has an exterior shell that adapts to the weather Geere (2015), and accommodates various climatic conditions and regional weather patterns Grozdanic (2015), making normal smart homes seem incredibly stupid Geere (2015). Despite being huge, the buildings' moveable components are lightweight and can be opened by hand Grozdanic (2015), while the residing quarters are made completely of glass Abendroth (2017).

Figure 10

Figure 10 (a) Shows the Design Exterior of Motus House and (b) is an Internal View of it Grozdanic (2015)

For instance, the living room is entirely made of glass Geere (2015), from the walls and ceiling to the floors Builder Online (2015). however, it can be automatically covered with various materials depending on the situation, such as an insulating shell or a sun-blocking covering as demonstrated in Figure 11 Geere (2015). This concept created a house that kind of opens up to the environment rather than having extremely thick, insulated walls that are opaque and prevent users from seeing outside or within Builder Online (2015). Additionally, the house offers flexible control over heat gain from sunlight, where sensors can detect a cold day and close both to keep the heat inside. And also, instead of cranking up the air conditioning on hot days, again this futuristic structure's shell surrounds the interior to keep occupants cool Abendroth (2017). As for sun lighting, the screen or shell can be changed to accommodate the light desired in the area Geere (2015). Where specific areas can be opened to let in sunlight or slid in and out to give shading Grozdanic (2015).

Figure 11

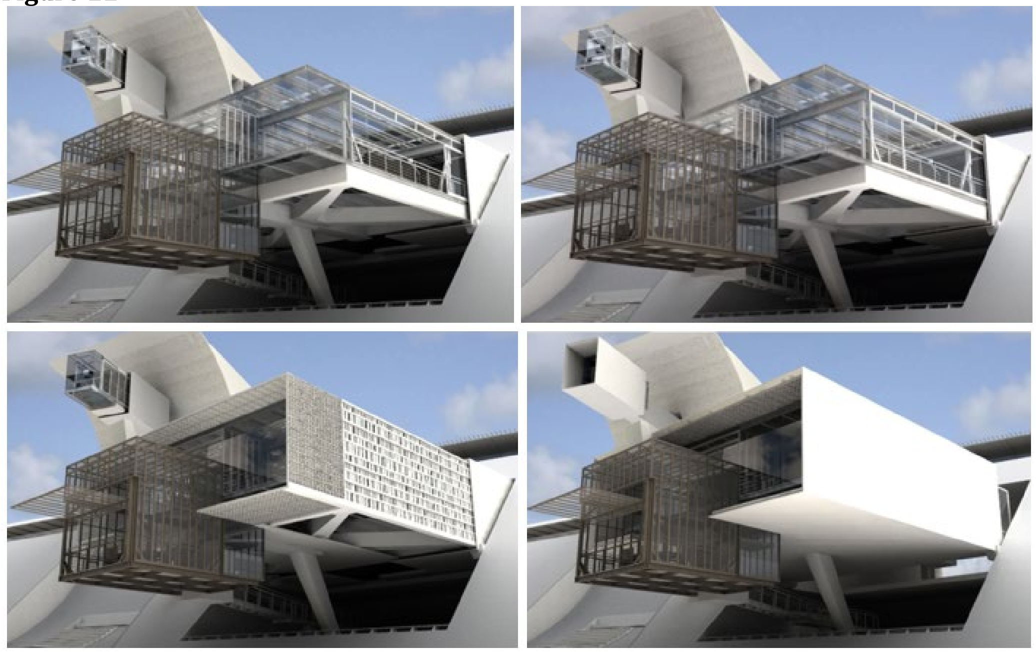


Figure 11 (a), (b), (c) & (d) Illustrates the 4 stages forming the layers of the building shell WritingHouse (2012).

Additionally, a system of solar panels powers the house and the device that raises the screens Geere (2015) and controls the moveable components that automatically open and close Grozdanic (2015). While a microclimate pool beneath provides cooling on hot days of the summer through evaporation Geere (2015). As for the roof, it offers space for a garden Abendroth (2017). Finally, and for now, this project is still a prototype. But it's going to set a new standard for houses everywhere Abendroth (2017). However, it's not inexpensive Geere (2015). The Motus house has a number of high-tech components designed to create a dynamic atmosphere without the need for heavy, static walls, ceilings, and flooring Grozdanic (2015). Thus, it is estimated that construction could cost between 3.5 and 10 million $ Geere (2015).

3.2. 4D PRINTING

Definition

The term 4D printing seems to be used more often these days Cassaignau (2016), and scientific studies have been supporting its revolutionary nature Sculpteo. (2023). It is a term used to describe a technique that enables the creation of objects with the use of 3D printing Cassaignau (2016). The created objects will change their shape once they are created Cassaignau (2016) into different shapes under the impact of external input such as light, temperature, or any other stimuli from the environment Sculpteo. (2023). For example, when submerging objects in water or when the temperature is lowered Cassaignau (2016). Thus, 4D printing is 3D printing plus time, where a 3D printed structure's shape, property, or functionality can change over time Momeni et al. (2017) .

Process and Advantages

The process of creating an object using 4D printing is not so much different from 3D printing. Where commercial 3D printers, including Polyjet 3D printers, are also used in 4D printing technologies. One of the main differences is the material used. In 4D printing, the input is a smart material, which can be either a hydrogel or a shape memory polymer which differs from the typical 3D printing materials in that it can alter its shape. Therefore, rigidity is a feature of objects produced using 3D printing technology, by maintaining their shape after being printed Sculpteo. (2023).

The most significant advantage of 4D Printing is its capacity to change shape over time as shown in Figure 12. It also allows size-changing that enabled a single-part printing of larger-than-printer objects with the help of computational folding. Since, the ability of 4D printed things to change shape, contract, and unfold allows for the 3D printing of objects that are too huge to fit in a printer by compressing them into their secondary form. Another very important advantage of 4D printing is developing new materials with new properties since it utilizes potentially useful materials. Multimaterial shape memory polymers have been the subject of experiments up to this point. Finally, some current potential applications of 4D printing besides architecture are; Self-repair piping systems, Self-assembly furniture, XLarge 4D printing in extreme conditions, the Medical industry, and Fashion Sculpteo. (2023).

Figure 12

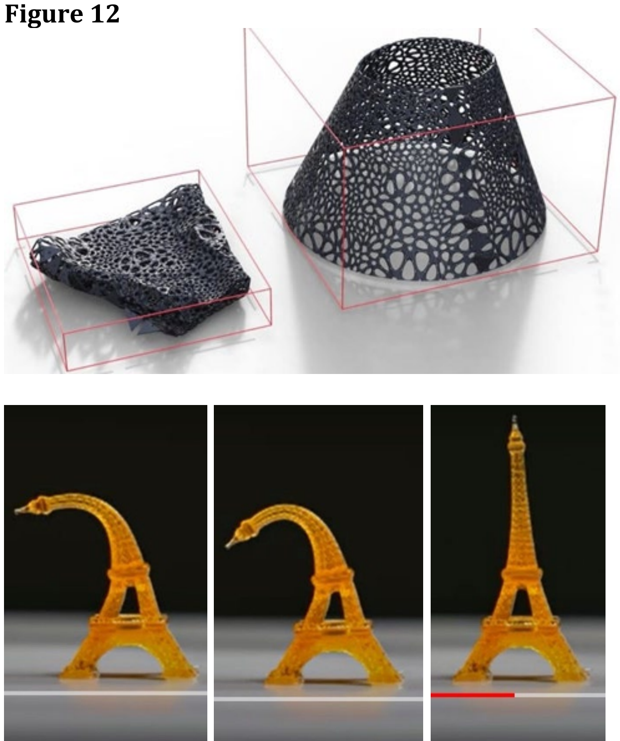


Figure 12 (a) 4D Printed Material Changes Size While (b), (c), & (d) is a Type of Shape Memory Polymer Showing its Changing Ability Sculpteo. (2023).

4. DISCUSSIONS

4.1. THE RELATION BETWEEN SHAPE-SHIFTING ARCHITECTURE & 4D PRINTING

As previously mentioned, in recent years, adaptive buildings that respond to environmental and climatic variables, such as light, wind, temperature, and humidity, have begun to be designed and built. This trend is rising in popularity due to the enhanced production and productivity they provide Garani et al. (2020).

And, in the aforementioned applications, a building's ability to shift shape is caused by allowing changes to the structure, the building's exterior, or the shell in response to one or more stimuli Chu et al. (2020), through using mechanical or electrical systems. It is accomplished by employing sensors or manually adjusting, which occasionally necessitates consuming a lot of energy. This does not mean it is the sole option, though. Shape-shifting can occur also throughout using morphing materials that can alter their shape in response to environmental conditions or according to human needs. This type can create autonomous responses to changes in the weather for example, without requiring any mechanical or electronic control or operational energy source Menges et al. (2013). This can be achieved at the level of a single building component or on the scale of the entire building; as will be further discussed in the next section.

From that, it became clear that 4D printing's role is being a tool for developing shape-shifting architecture by creating shape-shifting materials. Where it is believed that the best answer for all mechanical and electrical façade problems is 4D printing AbdElWahab and Abdelmasih (2023). It takes into account some of the shape-shifting behaviors such as folding, twisting, bending, surface curling, linear or nonlinear expansion/contraction, and the creation of surface topographical characteristics. These characteristics include folds, creases, and buckles Momeni et al. (2017). Furthermore, it is affected by external stimuli and interior stimuli. The major internal stimulus is cell traction force, while the main external stimuli are humidity, temperature, light, electric field, and magnetic field. Unfortunately, even though a variety of materials that respond to stimuli, including shape memory polymers and hydrogels, have been successfully tested for 4D printing, low efficiency and a sluggish response rate limit further advancement. This means novel smart materials still need to be created for 4D printing to progress further Chu et al. (2020). Furthermore, most current 4D printing technology is only responsive to a single stimulus; where printed structure alters in response to a specific stimulus. However, research is held to allow for multiple stimuli responses Ren et al. (2021). Finally, when applied to buildings it was found that up till now 4D printing is often used for items like facades, openings, and partitions. Hygroskin Meteorosensitive Pavilion, Bloom Pavilion, and Homostatic Building Façade are a few examples of projects that used 4D printing AbdElWahab and Abdelmasih (2023).

4.2. SHAPE-SHIFTING ARCHITECTURE TYPES

After analyzing many examples and information, the study classified shape-shifting architecture into two categories with four possible types. Category one is the shape-shifting building elements and category two is the shape-shifting of an entire building. Both can be achieved using shifting structures Garani et al. (2020) or materials Building Design and Construction (2014) as will be further explained below through the use of various examples. It was observed, that despite the fact that category one with both types accomplishes less than category two, in regard to fulfilling shape-shifting architecture goals, it is obvious that category one has received the most attention up to this point. Additionally, it appears that category two, which reflects the ideal shape-shifting architecture, is primarily made up of conceptual ideas or small-scale projects like pavilions. As a result, the study utilized the best-case study that, if not entirely, may represent them.

Category One – Type one: Shape-shifting Building Elements – Using Shifting Structures

The first category deals with a single shape-shifting element or component in the building such as adaptive facades Attia (2017) or dynamic façade Forestell (2022), movable walls Golenda (2017), openings, movable shells Pintosm (2020) or moveable roofs Cogley (2019), etc. Achieving this mechanically using the building structure represents type one as proposed by the study. The importance of these adaptive elements is that they can drastically improve energy efficiency and the utilization of renewable energy while also enhancing occupant comfort in buildings. These elements, especially the facades, can change on an hourly, daily, seasonal, or annual basis to accommodate changing weather conditions. Various existing projects integrating adaptive building envelopes are constructed worldwide Attia (2017). However, it must be highlighted, that not every adaptable building can serve as a shape-shifting building. For example, the AGC Building in Louvain La Neuve has an adaptive façade by using louvers that respond dynamically and automatically to the angle of the sun Attia and Bashandy (2016). In spite of that, it cannot be really perceived as going to the next level which is shape-shifting.

Thus, the first best example to explain this type is Al Bahr Towers in UAE Patowary (2015). This project consists of two towers that used an adaptive facade that falls under shape-shifting as demonstrated in Figure 13. Its construction started in 2009 and finished in 2012 Forestell (2022) with 56,000 m² that is mostly used for offices Attia (2017). The first tower has the headquarters of the Abu Dhabi Investment Council, while Al Hilal Bank has its headquarters in the second tower Forestell (2022). The twin buildings, which are 29 stories and 145 meters tall have a glass façade. Unlike any other glass façade towers, Al Bahr's façade is shielded by around 2,000 sunshades that resemble umbrellas and open and close on their own depending on the amount of sunshine Patowary (2015). Each sunshade weighs around 1.5 tons, and the total weight for each tower façade is around 1,573.5 tons AbdElWahab and Abdelmasih (2023).

Figure 13

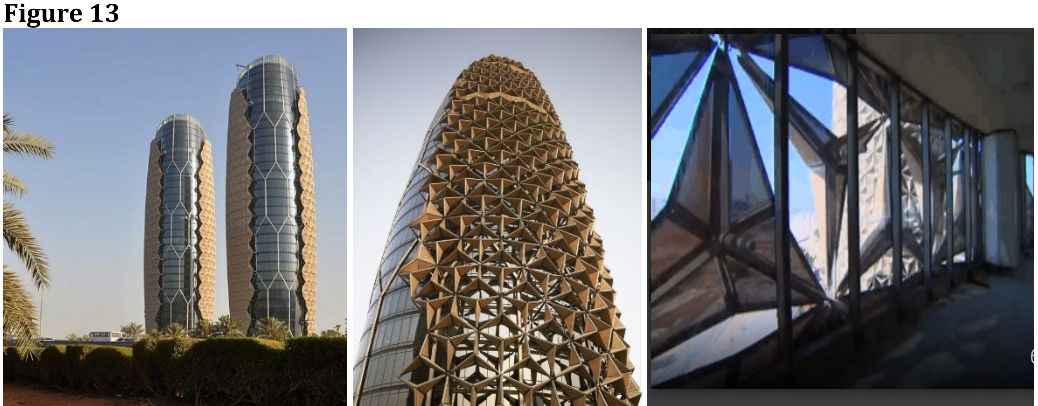


Figure 13 (a) A Far View of The Twin Towers When Sunshades are Closed, (b) a Nearer View to the Opened Sunshades, and (c) an Interior View of Closed and Opened Sunshades Tetex.com (2023).

These origami-like umbrellas which are made from triangular parts, make up the dynamic shading system of the screen Attia (2017) or so-called geometric skin Tetex.com (2023) as shown in Figure 14. These stunning elements are inspired by traditional Arabic architecture to ingeniously shade themselves from the sun Stem (2015). The inspiration came from the traditional wooden lattice screens known as "mashrabiya" that have covered the windows of traditional Arabic homes since the 14th century and offered shade and privacy while yet allowing residents to see the outside Patowary (2015). The automatic dynamic solar screen moves in a honeycomb-inspired structural design that blocks direct solar radiation by making the triangular units function as independent shading devices that open to different angles in response to the sun's movement Attia (2017). The ingenious design includes computer-controlled sunscreens that control the opening and closing as well as moving the screen horizontally Tetex.com (2023) to cover the light Stem (2015). Thus, this sophisticated design by Aedas Architects Tetex.com (2023) cut the heat from sunshine in the building by at least 50% and possibly lower the cost of air conditioning as well Stem (2015).

Figure 14

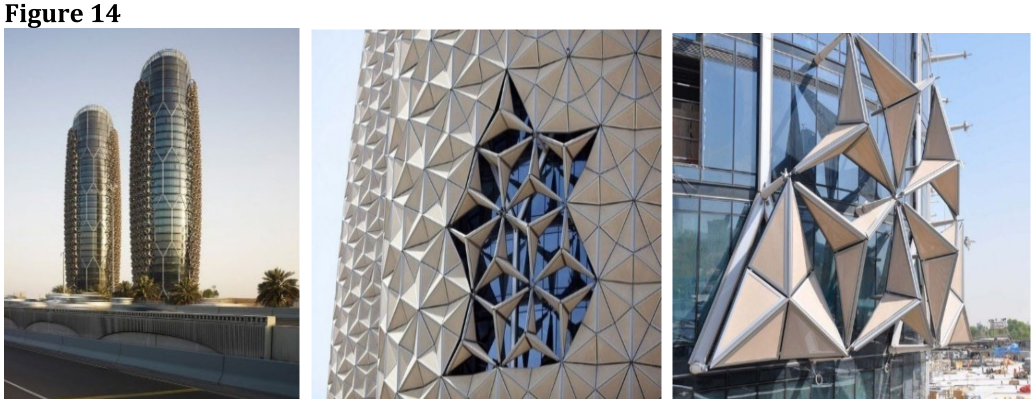


Figure 14 (a) A Far View of the Twin Towers When Sunshades are Opened, (b) and (c) are Nearer Exterior Views to the Opened and Closed Sunshades Patowary (2015).

On a separate frame, the outer skin is placed two meters away from the façade of the structure as demonstrated in Figure 15. Each triangle has a fiberglass coating and its vertical strip travels with the sun as it goes around the building in the morning when the sun rises in the east and the shade components along the east of the structure start to close Patowary (2015). At night the sunshades are folded to give more view of the facade. Additionally, the architects were able to avoid using dark-tinted glass, which invariably inhibits all incoming light constantly, thanks to the shade's capacity to filter light Patowary (2015) and let natural light into the building Attia (2017). As a result, there isn't as much artificial illumination inside Patowary (2015). Hence, the building had the ability to improve control over energy use, solar radiation, lighting, and glare Attia (2017). In total, the annual energy usage is around 400 watts/meter whereas a single mashrabiya needs 14.71 k.N. to move it AbdElWahab and Abdelmasih (2023).

These are the factors that made numerous architects and publications praise the two towers' creative and environmentally friendly design. It was also listed as one of the Innovative 20 structures that challenge the typology of tall buildings in the 21st century by the Chicago-based Council on Tall Buildings and Urban Habitats. Not only that but also the 2021 Tall Building Innovation Award was given to the towers as well for their innovative use of culture and urban planning as well as sustainable engineering Forestell (2022). Finally, experts consider this to be the tale of a famous building that transformed traditional vernacular Islamic architecture into something more contemporary Forestell (2022), and more advanced by creating a shape-shifting architecture.

Figure 15

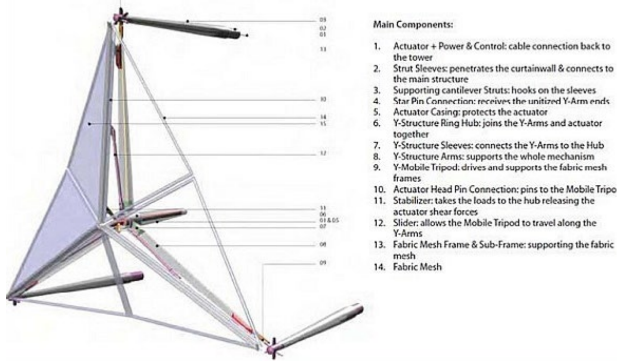


Figure 15 (a) A Precise 3d Illustration of the Shading Device Elements and (B) A Close-Up Showing Where the Strut Sleeves Enter the Wall and Join the Main Building Attia (2017).

Another great example is the project called the Shed in New York City area Scofidio and Renfro (2017) of Hudson Yards Ned (2019) illustrated in Figure 16. It is a nonprofit cultural organization that commissions, creates, and exhibits unique works of art from various disciplines for a variety of audiences Pintosm (2020). With 200,000 sq. feet in size Scofidio and Renfro (2017), the building is intended to serve as an interdisciplinary artistic hub that fosters a collaborative environment with open galleries, a creative lab, and a 500-seat theatre Ned (2019). The project was completed in 2019 Scofidio and Renfro (2017). According to the requirements and demands of the artists using the space, the building is designed to be adaptable and capable of physically changing itself Cogley (2019). Using a shape-shifting design strategy, the architecture firm Diller Scofidio & Renfro (DSR), and Rockwell Group created a flexible design that uses high-tech architectural elements Ned (2019). When necessary, the roof can extend and enclose the adjacent courtyard to maximize indoor entertainment spaces. This makes the roof and its structure adaptable, incredibly flexible and accommodating Ned (2019) that it could even alter size, on demand Cogley (2019).

Figure 16

Figure 16 (a) & (b) The Shed project that holds an artistic hub Ned (2019).

The Shed design features four, double-height levels known as two, four, six, and eight. Cogley (2019). Its telescoping outer shell can be lowered from above the foundation structure and moved over the adjacent plaza on rails Pintosm (2020) as seen in Figure 17.

Figure 17

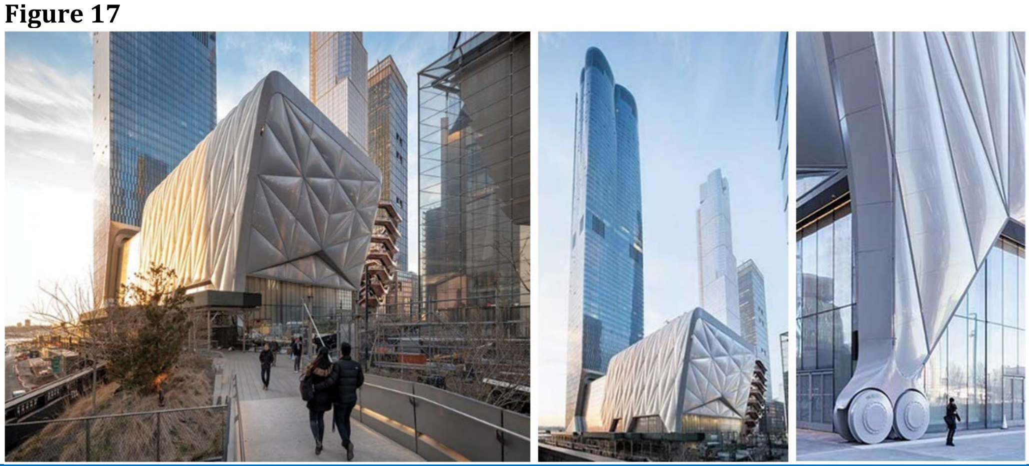


Figure 17 (a), (b), & (c) The Shed, As Seen from Different Views on Eight Bogie Wheels, The Building's Retractable Shell Rolls Out. Giovannini (2019).

The Shed's moveable shell is tucked within the nearby residential skyscraper, another building created by DSR and Rockwell Cogley (2019) as illustrated in Figure 18. The open infrastructure of it can adapt indefinitely to changes in scale, media, and technology as well as to the changing needs of artists. Its 37-meter moveable shell is constructed of an exposed steel diagrid frame and translucent cushions composed of ethylene tetrafluoroethylene (ETFE), a sturdy and lightweight Teflon-based polymer. This substance weighs a tiny fraction of insulating glass while possessing the same thermal qualities. Some of the largest ETFE panels ever made, extending nearly 21 meters in length in some places, were used in the Shed Pintosm (2020). Finally, the building was designed to surpass New York's energy codes by 25% and receive LEEDSilver certification Pintosm (2020). And at least initially, the majority of its $50 million operating budget will come from donations and revenue. Giovannini (2019).

Figure 18

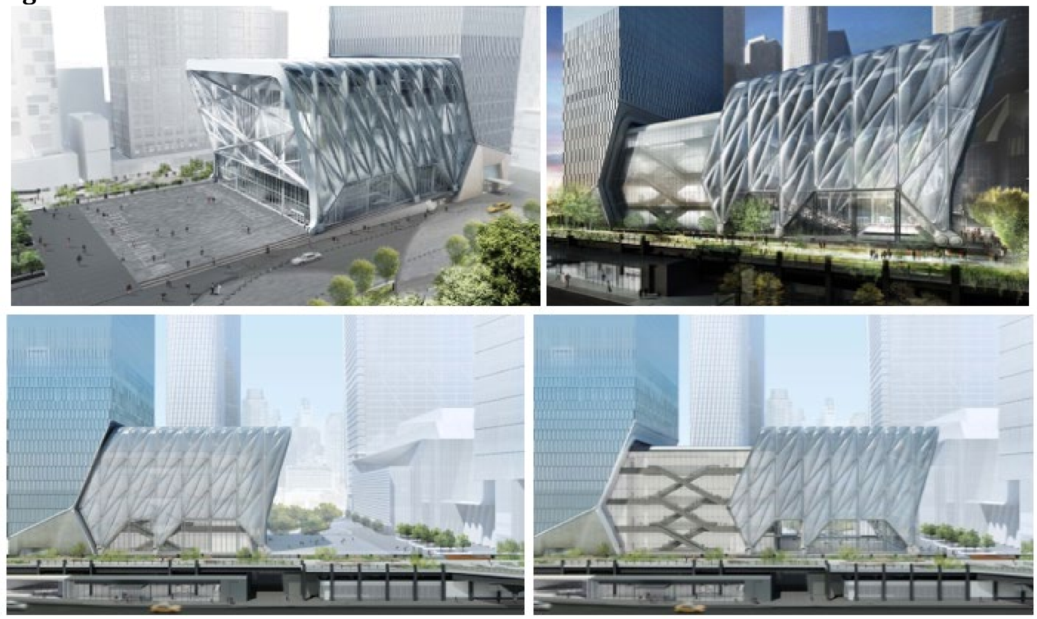


Figure 18 (a), (b), (c) & (d) Demonstrate the Moveable Shell and Its Relation to the Adjacent Building Scofidio and Renfro (2017).

Category One – Type Two: Shape-shifting Building Elements - Using Shifting Materials

Type two in the first category still deals with a single shape-shifting element in the building, but throughout using shifting materials. A great example to demonstrate this concept is the Hygroskin Meteorosensitive Pavilion. A revolutionary style of climate-responsive architecture is explored in this project Menges et al. (2013) which took it to the domain of shape-shifting. This project used the shifting capacity of the material itself Menges et al. (2013), which was wood in this case, in relation to humidity AbdElWahab and Abdelmasih (2023) and moisture as an external stimulus Menges et al. (2013). As demonstrated in Figure 19, the modular wooden skin of the traveling pavilion is created using the ability of originally flat plywood sheets to self-form conical shapes depending on the elastic behavior of the material Menges et al. (2013). It is possible to physically program the produced material to compute various forms in response to variations in relative humidity Menges et al. (2013) using folding adaptability AbdElWahab and Abdelmasih (2023). The apertures react to changes in relative humidity between 30% and 90% Menges et al. (2013). The closing and opening of this element neither require mechanical systems nor consume any energy.

Figure 19

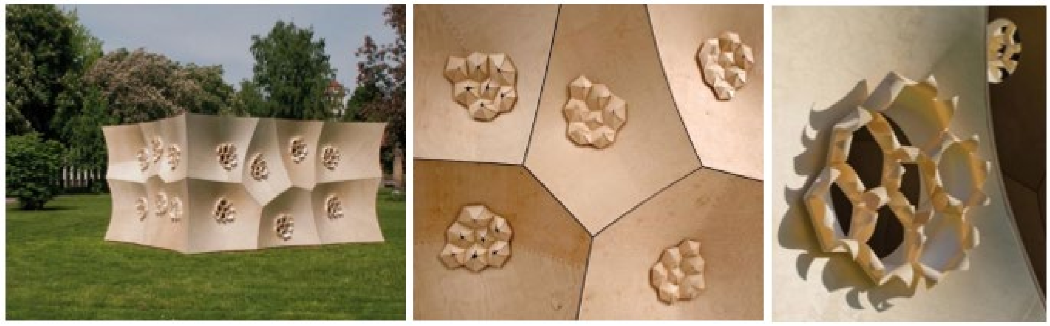


Figure 19 (a) The Hygroskin Meteorosensitive Pavilion, (b) its Conical Shapes When closed, and (c) When it is Opened Menges et al. (2013).

Category Two – Type Three: Shape-shifting of an Entire Building - Using Shifting Structures

Category two represents more sophisticated and desired types of shape-shifting architecture. It deals with the morphing of the entire building and not only a single element or part of it. Type three, that the study proposes, achieves this through using the building structures. Although it is still a conceptual design and has not yet been put into use, a great example of this type is the Dynamic D* Haus house Garani et al. (2020). It is a promising shape-shifting building Garani et al. (2020), that was first unveiled in 2012 Gibson (2017) and reacts to time and weather conditions Garani et al. (2020). The house was initially created by David Ben-Grunberg as his graduation project to withstand seasons of extreme temperatures Gibson (2017); the intensely cold winters and mild heat summers in Lapland Frearson (2012). However, the idea has since been refined such that the house could be utilized anywhere in the world Frearson (2012). And Grunberg and Daniel Woolfson created this shapeshifting home demonstrated in Figure 20 that changes depending on the season and even the time of day in the UK Lieff (2017). They relied on a mathematical formula, developed by Henry Duden, that determines how many equilateral triangles can be used to construct a square as the foundation for the house's geometry and movement Gibson (2017).

Figure 20

Figure 20 (a) & (b) Outer Views of the Dynamic D* Haus House **Lieff (2017)**.

The structure was divided into four distinct modules Garani et al. (2020) that come together to make a perfect square in the plan Gibson (2017) as demonstrated in Figure 21. The initial shape can be rotated and inclined to generate eight new shapes Garani et al. (2020). The house rotates throughout the year to follow the sun Lieff (2017), moving along rails, opening up during milder seasons, and closing in during more severe weather Gibson (2017). Thus, it shifts into triangles in the summer and collapses back into a square in the winter to retain heat. Where interior partitions turn to become exterior walls, doors become windows, and windows into doors as the house literally reconfigures into the eight shapes, going from a square to equilateral triangles Lieff (2017). For example, during warmer months, rooms would fold out on rails to become outdoor walls, and the entire structure would be able to rotate to track the position of the sun throughout the day Frearson (2012)

However, E.J. Meade, a Boulder architect, notes that the design has not yet been executed and that there are inherent issues. He believes in the visionary, but getting a building to stay put is really difficult. Smaller-scale operational components are much more realistic to him. Lieff (2017). Even Woolfson stated that they were still debating how it would operate in real Frearson (2012). However, David addressed the RIBA and asked if they would recognize the project. Together, they pioneered the ''RIBA Host Practice Scheme DHaus. (2012).

Later on, a house with a rotating roof has been created for a location in Devon, England by the same architects using an updated version of their shape-shifting D*Haus Gibson (2017). It was a less expensive and static version of the same design Gibson (2017). They also needed to maximize the 270-degree vistas offered by the steep site, so they included a glazed prism-shaped volume placed on a revolving circular platform Gibson (2017). Unfortunately, the need to create a more static version casts doubt on the capacity to ever put the dynamic shape-shifting version into practice.

Figure 21

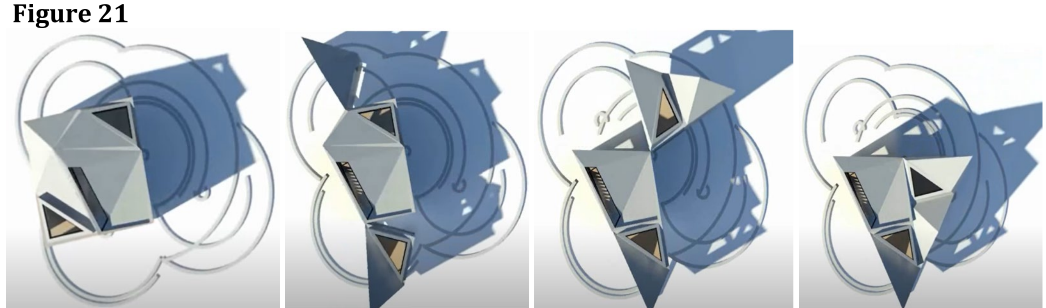


Figure 21(a), (b), (c), & (d) The Shifting Movement of the House From Square to Triangle **Architects (2014)**

Another example of the third type is the Safe House. It is the home of Polish architect Robert Konieczny outside of Warsaw Golenda (2017). The building was constructed from 2005 to 2009 on a site area of 2500 m2 and a usable floor area of 567 m2 Frearson (2012), in Poland's suburbs Garani et al. (2020). The house changes from a day villa to a night fortification as demonstrated in Figure 22. The client's ultimate aim, which influenced the building's design and functionality, was to feel as secure as possible in their future home Frearson (2012). Therefore, to reduce the likelihood of a break-in, the entire facade and windows are covered with wall panels Garani et al. (2020) and retractable shutters Golenda (2017). This allows the house to close down into a secure central core with a drawbridge Golenda (2017). It behaves consistently each day, waking up in the morning and shutting down at dusk. This routine is reminiscent of natural processes since it makes the house look like a plant going through its day and night cycle Frearson (2011). The house assumed the shape of a cuboid with moveable external walls.

Eastern and western side walls shift toward the outer fence to create a courtyard as the home opens up to the landscape. One must wait in this protected area after passing through the gate before being allowed inside the house. At the same time, there is no danger of kids playing in the garden escaping in an uncontrolled manner to the street area Frearson (2011).

Figure 22

Figure 22 (a), (b), & (c) Shows the Safe House; a Villa by Day and a Fortress by Night Frearson (2012).

Both of the sliding walls are 2,2 m high, and 22 and 15 m long. They are the most important since they help define the plot's safe zone. In addition to these, there is a drawbridge leading to the roof terrace over the swimming pool as seen in Figure 23, and a set of tall shutters; all are 2,8 m high, with widths ranging up to 3,5 m, and opening up to 180 degrees. A large roll-down gate measuring 14 and 6 meters closes the southern elevation. It can serve as a movie projection screen because it is made of white anodized metal. All of the moving parts are powered by internal electronic engines that ensure their safe operation Frearson (2012)

Figure 23

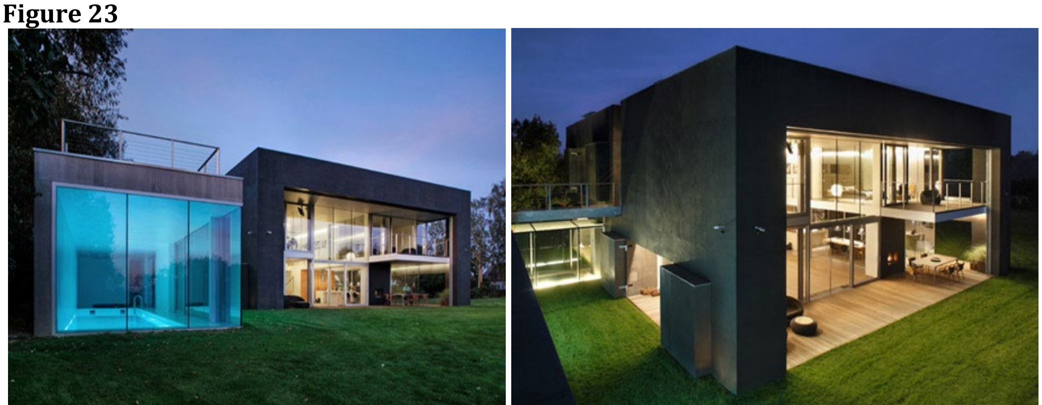


Figure 23 (a) The Building with a Swimming Pool and (b) Shows the Connected Drawbridge Frearson (2012).

The entire structure is made of concrete, and its mobile components are mineral wool-filled light steel trusses for size reasons. Cement-bonded particleboards (Cetris) and waterproof alder plywood are fixed to a steel frame and painted with a dark wood stain to resemble the wood commonly found on the nearby houses and barns. This blends the house with the surrounding rural landscape. Wide windows behind the moveable walls allow the structure to gain energy throughout the day (in the winter) or block the heat from the sun from entering the home (in the summer) Frearson (2012).

Category Two – Type Four: Shape-shifting of an Entire Building - Using Shifting Materials

The fourth type is regarded as the most complex and challenging of the four. It is creating shape-shifting architecture for the entire building using shifting materials. Finding a good example to represent this type, even conceptually, was really challenging. This indicates that technology still needs to advance in order to discover more innovative concepts and applications for this kind of architecture; else, it will only exist as a theory. The Bloom Pavilion, however, is a case study that can somewhat exemplify this kind of concept. The basic concept behind it is a self-adaptive, active, zero-energy interface. The team made a pavilion with 414 units that had bimetallic sheets that wrapped and provided shading when exposed to sunlight using two layers of metal that react differently to heat as demonstrated in Figure 24 AbdElWahab and Abdelmasih (2023).

Figure 24

Figure 24 (a), (b), & (c) The Bloom Pavilion and its reaction to sun and heat Furuto (2012), Sung (2012).

Shape-shifting Architecture in Relation to Sustainability & Developing Countries

Adaptive architecture, movable dynamic architecture, and echo-tech smart architecture are a few examples of previous concepts that appear to be the cornerstone in forming the emerging shape-shifting architecture. The multiple applications reviewed made it obvious that it aspired to be sustainable by modifying its shape to accommodate its environment and users' needs while maintaining functionality. Its sustainability scope addressed topics including reducing energy consumption by controlling solar gain and loss in the winter and summer, managing natural lighting and shade, meeting human requirements, etc. If this could be accomplished for the entire building, it would be the realization of every architect's ambition. It appears that is not the case, though. Despite the fact that the term "shape-shifting" has been around for at least a decade, there are still relatively few examples of it in the world, most of which are just conceptual designs. In light of this, it is fair to suggest that although shape-shifting architecture is an excellent concept for achieving sustainability, its' incredibly slow progress may cause some to doubt its viability as a practical solution. Where the world today needs a method of sustainable architecture that promotes productivity, can be applied on a broad scale globally, and is feasible to build. In other words, it must be doable. However, in many of its designs and concepts, operating systems, special construction, and materials are listed as expensive options along with operational costs and the price of any potential modifications AbdElWahab and Abdelmasih (2023). This is far from what is required nowadays.

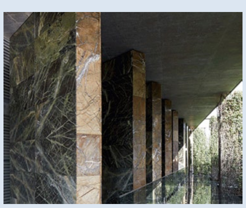
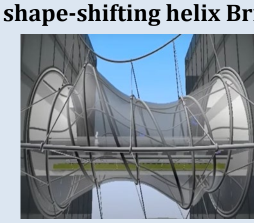
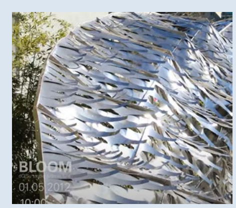
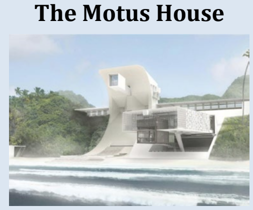
Finally, unless urgent measures are taken, and more technological breakthroughs happen, it is anticipated to not see a real shape-shifting architecture spreading particularly in developing countries any time soon. And in that case, it is expected that the shape-shifting element category would be more usable, but with few applications. There are additional challenges that will arise in developing nations than those already stated. They will also encounter issues with efficiency, skilled labor, availability, maintenance, economics, etc.

5. CONCLUSIONS

Shape-shifting architecture is a futuristic approach to achieving sustainability. It is defined as the ability of a building to change its shape to another shape due to certain stimuli and adapt to environmental and human needs. It was discovered that some applications of responsive, adaptive, or dynamic architectures fit the definition of a shape-shifting architecture. That is because shape-shifting architecture evolves from being responsive and adaptive to the environment as illustrated in the study. As a result, it evolved into being a flexible, dynamic, and extremely intelligent sustainable architecture to achieve its goals. The study was able to propose a classification of it, where it has four types that undergo two categorizations as illustrated in Table 1.

Table 1

Table 1 Shape-shifting Architecture Classification

	Category (1) **Shape-shifting Building Elements**		Category (2) **Shape-shifting of an Entire Building**	
	Type (1) Using Shifting Structures	**Type (2) Using Shifting Materials**	**Type (3) Using Shifting Structures**	**Type (4) Using Shifting Materials**
Its complexity	The easiest and the most commonly used type in buildings.	It is still emerging and used in pavilions.	It is complex and still has its best examples in the conceptual stage.	The most sophisticated and hard to achieve.
Main Tool	Smart Systems	4D Printing	Smart Systems	4D Printing
		Applications		
Example (1)	**A Residence in India**  Constructed	**The Hygroskin Pavilion**  Constructed	**A shape-shifting helix Bridge**  Conceptual Design	**The Bloom Pavilion**  Constructed
Mechanism	Shifting Walls	Shifting Openings	Shifting Form	Shifting Envelope
Example (2)	**The Sharifi-ha house**  Constructed		**The Motus House**  Conceptual Design	

Mechanism	Shifting Rooms		Shifting Envelope	
Example (3)	**Al Bahr Towers**  Constructed		**Dynamic D* Haus House**  Conceptual Design	
Mechanism	Shifting Screen		Shifting Form	
Example (4)	**The Shed**  Constructed		**The Safe House**  Constructed	
Mechanism	Shifting Roof		Shifting Envelope	

It is obvious that type one is the most prevalent type and type four is the least common. That is because materials-based shape-shifting still requires significant development. However, this is not the only obstacle that hinders its advancement, especially in developing countries. Other factors were observed as potential issues, such as efficiency, skilled labor, availability, maintenance, economics, etc. Furthermore, it appears that all applications worked in relation to energy, lighting, shading, temperature, ventilation, air quality, views, function, size, and safety. However, much more is still expected from this architecture in the fields of water efficiency, recycling, and other adaptability approaches. Thus, it is fair to say that shape-shifting architecture is still in its early stages even a decade later.

CONFLICT OF INTERESTS

None.

ACKNOWLEDGMENTS

None.

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