3D printed house: the digital transformation in architecture and construction of the Sustainable Houses

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Abstract:

There is an increasing demand for sustainable, and dignified housing in the building and construction sector, particularly in developing countries with limited resources, growing energy consumption, population, and CO2 emissions. Therefore, the adoption of digital design, construction, and innovation technology is vital; one of these technologies is 3D printing (3Dp), which has become a recently essential and powerful technology in the construction industry. As such, 3Dp has advantages and potentials over traditional housebuilding in that it can use robotics, software, and advanced materials. The paper investigates the Potentials and limitations of 3DP adoption on digital design and Construction housing projects. Moreover, review and analysis of 3D Printed Houses for evaluation of their performance and future usage capabilities. The study concludes that 3DP technology appears to be a promising alternative to enhance design and construction process performance, address various aspects of advanced materials, affordability, and sustainability, including social and economic aspects. The paper's objectives started with investigating 3Dp adoption in AEC by highlighting the advantages and potentials of 3Dp for sustainable housing. Furthermore, the challenges of 3Dp in Architecture and Construction are discussed.

Keywords:

3d printing; digital design; digital architecture; sustainability.

1- Introduction

According to a United Nations global survey, the construction industry accounts for nearly 40% of global energy consumption and CO2 emissions (UN 2017). Construction firms are aware of the potential of new technology to boost productivity, save resources, reduce costs, project duration, and at the same time reduce materials consumption, because traditional construction methods suffer for a long time from constraints and problems without taking severe steps or action to solve these problems (Ramirez 2020). Until the Fourth Industrial Revolution, which is known as industry 4.0, which encouraged digital transformation in the construction industry and the adoption of advanced digital methods (Freire T 2021; El-Sayegh 2020). There is still a strong demand for housing, which has many problems. Some are related to the high cost of construction, sustainability, the gap between supply and demand, and design options, said Jason Ballard, co-founder and CEO of ICON (Hickman 2021). Many countries worldwide adopt and apply 3Dp technology to create large-scale structures and specific projects (ICON 2019), including administrative buildings, houses, exhibitions, and implemented using developed materials, digital programs, and robotics. 3Dp is one of the main trends toward the digitalization of the construction industry (El-Sayegh 2020; Park S 2016), which can upend traditional

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construction, and its application in construction projects has been growing. 3Dp is a promising solution to the common problems of this industry (Mahadevan 2020), because of its freedom in geometry, rapidness, formwork-less printing, low waste generation, eco-friendliness, cost-saving nature, and safety (Kaur G 2021). 3Dp has been hailed as a fast, cheap, environment-friendly way to build sustainable housing (Ramirez 2020).

The paper's objectives started with investigating 3Dp adoption in AEC by highlighting the advantages and potentials of 3Dp for sustainable housing. Furthermore, the challenges of 3Dp in Architecture and Construction are discussed.

The objectives are arranged through the following questions:

- How can 3D printing be a solution to getting sustainable housing?
- What are the maximum potentials of 3Dp for digital Architecture and Construction?
- What challenges will limit the adoption of 3Dp?

The research methods mainly depended on three sections as follows:

- A literature review explains the Potentials and limitations of 3DP adoption on digital design and Construction housing projects.
- The analysis of 4 case studies for 3D printed houses built in the construction field between 2018 and 2020. Each project presents significant practical application of 3d printing methods, developed materials, designs, environmental solutions, methods to reduce resources, innovated solutions to get sustainable housing.
- The SWOT analysis of 3D printing technology, which highlights the technology's strengths, weaknesses, opportunities, and threats. It is emphasized that doing a SWOT analysis of 3D printing using various methodologies is beneficial for evaluating and highlighting its practical capabilities.

2- Literature Review

3D Printing Technology in AEC Industry

In 1984, Charles Hull developed the first printer. While, Carl Deckard invented the selective laser sintering printer in 1987 at the University of Texas. SLS is a technique for 3D printing products that involves sintering a powder bed using a laser. (Truong 2019). Since the 1990s, 3D printing has evolved as a result of previous additive manufacturing research and production (Truong 2019; El-Sayegh 2020; Wu H, 2018). 3D printing technology that has developed into an industry trend and impacted a variety of industries, including manufacturing, healthcare, and construction. Anything is possible to print in three dimensions, and all that is required is a digital file (CAD file) or a three-dimensional digital model (BIM model) (Noorani 2017). In the housing industry, 3D printing can fabricate structures with almost no waste, minimal costs, and a shorter build time. Depending on the complex and scale of the structure, it can be completed in a matter of days, a replacement structure is frequently constructed, which is customised for each iteration of the building. 3D printed houses can be constructed in a variety of ways and with a variety of materials. Each method of construction necessitates a unique printer model, materials, and advantages and disadvantages (Truong 2019). 3d printing or additive manufacturing has become a significant part of many manufacturing ecosystems (Amorim C G 2021), which have been developed reliable technologies, materials, robotics, and machines for more growth. From prototypes and simple elements to highly technical final products, for example, aeroplane components, medical implants, and even artificial organs used for humans, as well as construction (Ramola M, 2019; Laovisutthichai V 2021). Referring to the State of 3D Printing report, 2020, 3D printing is becoming more critical and allowing additive manufacturing to evolve. (Gaget 2019).

Digital Transformation of Architecture and Construction

Emerging digital technologies have begun to influence central issues in Architecture and Construction and associated industries, including using robotics, software applications, digital design, digital materials, computing equipment, and digital machines (Van Winden 2017; Oxman, R. 2008). 3D technology grows, 3Dp can disrupt the traditional architecture and construction processes. 3d printing has revolutionized the AEC industry. Indeed, as a result of the advancement of digital technology, design, applications, software, and programs, for example, are beginning to play an essential role in today's architecture; design has become rich in ideas, complex free forms, shapes, structure, and complex topographical models that were previously difficult or unavailable (Oxman, R. 2008).

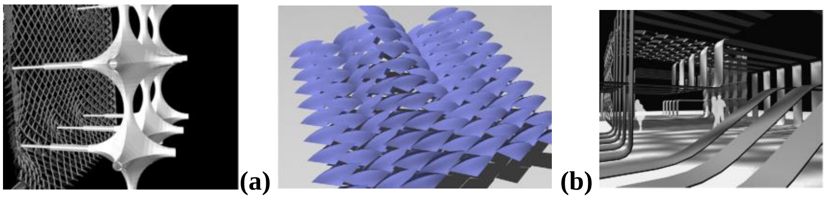
(a) (b) (c)

Figure 1. Some forms resulted from digital design and unlimited potentials, (a, b) by Shoham Ben Ari and Roey Hammer, Technion IIT, (c) by Alex Eitan and Tal Kasten, Technion IIT

3D printing and digital Architecture

The first step for DAD is the digital models. Creating a digital version of the project components can provide many benefits and new design opportunities. Designing for 3D printing is an entirely different process than designing for traditional methods; it will also need to identify the technology by analysing the project's performance requirements. Today, there exists a wide range of digital tools for simulation, analysis and evaluation of performance aspects that provide generative and modification capabilities such as simulations that can directly modify designs (Chaszar 2006). Moreover, BIM is a powerful application for the 3D printed building movement to govern the design (Sakin and Kiroglu 2017). BIM refers to the interactions between proceedings, processes, and technology that provide an approach for architecture, engineering, and construction (AEC) industries. BIM presents the project information in a 3D model and a digital format (Omayer M 2021), which support more efficient methods of designing, creating, and maintaining the built environment and construction process (Sakin and Kiroglu 2017). Complex designs that could model using BIM complicated with traditional methods; the integration of BIM with 3Dp techniques is now possible with digital manufacturing, allowing you to get better-performing parts, leading to significant cost-saving in terms of design.

The advantages of 3D printing for digital Architecture

Not only can 3D printing use creative and unique designs and models, but it can also improve the usability of software and printers. The benefits of 3D printing technology for the digital architecture stem from the evolution of digital technologies, programming, and applications

(Carolo 2020; 3dsourced 2021; Burnsocial 2020; Kaur G 2021). The majority of these benefits can be summarized as follows:

- Almost everything designed in 3D format can be 3D printed, which is the pinnacle of invention. This aspect of 3D printing distinguishes it as a highly professional tool for 3D print visualisation model architects.
- Human mistakes are eliminated with 3D printing. High accuracy; if the model's concept evolves, we can alter the 3D model and 3D print it again.
- Complex designs of all shapes and sizes can be created using 3D printing, which allows for a high level of detailing. 3D printing can build the entire structure much faster than piecemeal construction.
- Freedom to design, generative design, flexibility in structural geometry, Create unique designs. 3D printing allows designers to create complex forms without having to worry about how to assemble complicated models.
- Highly precise and accurate, 3Dp can print very thin layers (0.06 mm), with high quality finish, the 3D printed architecture model would highly resemble the concept.
- High quality, and add new functionalities to the product. The designer can reach a higher level of professionally using new 3D printing opportunities such as Selective Laser Sintering or Jet Fusion without any support. The model easily can be printed directly from the printer.
- Create integrated assembly, reduce the number of components, and optimize the component to make it even more efficient and adapted to its use.
- Additive Manufacturing will speed up the production process of your model, which is especially important with advanced models. Architectural concept models in 3D are becoming commonplace, and they may be easily optimised for 3D printing.
- Get lighter and more robust components, thanks to innovative design structures.
- If your project changes, all you need to do is adjust the 3D file according to your needs and reduce the cost of the project, which is usually not the case with traditionally manufactured models.
- Many choices of materials are available, assisting the designer in presenting his design in different ways and formats, any part he wants to display or print with multiple levels of details, materials and colours, thereby helping stakeholders to visualize the final product of the design or project in its final form.


(a)

(b)

(c)

Figure 2. The faster and low cost 3D printed houses around the world (a) Apis Cor 3D printed house, in just 24 hours with $10,000, Russia. (b) ICON & New Story 3D printed house in 24 hours, with cost of $10,000, USA. (c) The First family move into a 3D printed house in France, with almost price of: $170, 000, in 54 hours (Carolo 2020; 3dsourced 2021).

3D Printing Applications in Construction Housing

According to Mahdi the printed house refers to any modern structure in which materials are spread in layers according to digital file format to generate a 3D model in a real size (Mahdi R M. 2021). Winsun, a Chinese company, is a market leader in 3D printed houses. In 2015, Winsun demonstrated its 3D printing capability by printing ten houses in record time, in less than 24 hours. Additionally, Winsun 3D printed a six-story building (Truong 2019). XtreeE Company integrated house components in 2017 via 3D printing a wall with a window. The wall is constructed using robotic arms that can work in tandem. The sequence of multitasking construction is a technological advancement in automated construction (XtreeE 2019). ICON moved to the construction site using a gantry printer with a 2000 square foot building area. Houses are printed in their entirety, which results in increased thermal insulation and a more even distribution of structural stresses caused by earthquakes and hurricanes (Truong 2019). While a gantry printer's building size is limited, the gantry mechanism enables the pickup and placement of heavier objects. The following 3D printed houses built in the construction field between 2018 and 2020. Each project presents significant practical application of 3d printing methods, developed materials, designs, environmental solutions, methods to reduce resources, innovated solutions to get affordable and sustainable housing. The projects selected to reflect the evolution of 3D printing technology in both architecture and construction.

Prvok the floating house

In 2020, Prvok, or the floating house, is the first 3D printed house in Ceske Budejovice, Czech Republic, designed by Michal Trpak with the support of Scoolpt architects. This house's 3D printed walls have green sustainable roofing, allowing for incorporating water recovery systems. Prvok is divided into three spaces: a bedroom, a bathroom, and a pantry. The printing of the house took 48 hours, 25 labourers, and 17 tonnes of the custom concrete mixture. According to the company reports, the 3Dp walls are at least three times stronger than regular concrete walls. A robotic arm that had previously been used on an automotive assembly line and had been modified and reprogrammed for this house built the 3D printed house. A concrete mixture enriched with Nano-polypropylene fibres and substances to enhance plasticity and speed drying used. As 3D material, mixture concrete has numerous opportunities. It can be moulded, reshaped, sprayed, cast, and layered (Carolo 2020; Ramirez 2020; Designboom 2020).

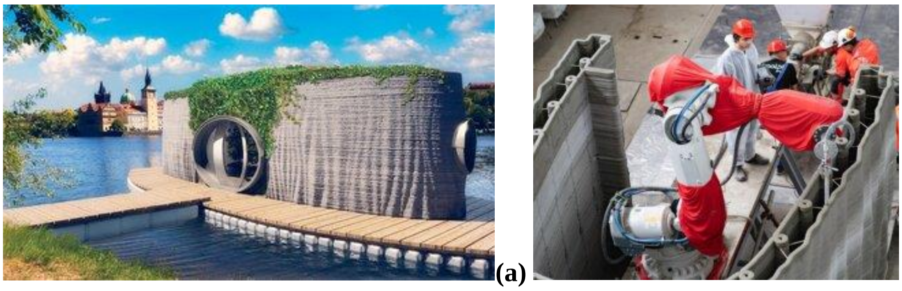
(a) (b)

Figure 3. (a) Prvok or the floating house (Carolo 2020), (b, c) The Scoolpt robotic arm printing the house, (Ramirez 2020).

Curve appeal

Curve Appeal, also identified as 3D House, is the first freeform 3D printed home in the world. The amazing conceptual 3D printed house designed by the Urban Architecture Studio of design consultancy firm WATG and completed in Chattanooga in 2020 (WATG 2020). In June 2016, the design won a prize in The Freeform Home Design Challenge. The design, which is the first of its kind, is inspired by organic structures, with the facades, roof, and interior made up of 28 different panels that were 3D printed off-site. The house features a sweeping curved exterior that is simple in design and offers structural stability. The approximately 240-square-meter house has a unique shape and design aid in keeping its interior comfortable throughout the seasons. Furthermore, the structure takes advantage of innovative technologies and applications, for instance, solar carving and passive mechanized systems to save energy. Except for traditional 3D printing, which moves within just a limited direction, Curve Appeal uses cutting-edge robotics to create customized shapes and extreme curvatures, resulting in increased efficiency, low cost, high creations with maximum structural stability (Annappa V 2021; WATG 2020).

Figure 4. First 3D printed house with a smart system in the world, (WATG 2020).

The DFAB House

The DFAB House near Zurich is the world's first 3D printed house with an intelligent home system, and it was designed and built entirely with digital technology, from digital design to robotics in construction (Rose 2019). The house consists of three levels. The most important features are the energy-efficient walls, 3D printed roof, and timber beams, with 220 square meters. At ETH Zurich University, over four years, a team of university experts with 30 industry partners were formed to develop the house and reduce 60% less cement. DFAB House has stringent Swiss Building safety codes (Quito 2019). This 3D printed house is the product of experts, architects, and engineers working on the merger of digital design and additive manufacturing in several fields, such as developed materials, software, and robotics. This enormous effort has increased building and construction efficiency, as well as more affordability and sustainability aspects. For example, cement production recently represents almost 8% of the global amount of CO_2 emissions. Therefore, one solution was to optimize the digitally planned floor slab and reduce the considerable material compared to the traditional concrete slab (Rose 2019). Digital architecture has many potentials for meeting changing societal needs and environmental challenges and enhancing the sensibility of beauty and creativity in architecture. An example of the 3d printing method's possibilities is the DFAB House's decorative ceiling built using a large-scale 3D sand printer. Using robotics onsite can even provide a better workplace environment and increased safety and health (Quito 2019).

 (a)  (b)

Figure 5. (a) DFAB house presents the innovative digital technology from research to architecture, (b) spatial timber assemblies (Quito 2019).

The biggest house

3D printing technology has made significant progress since its beginning. In 2019, the USA decided to build the biggest 3D printed house in the world using SQ4D and its Revolutionary Autonomous Robotic Construction System (ARCS). The biggest house has a total area of 175-square-meter on Long Island, USA. The 3D-printed house was printed and completed in only 48 hours of print time. SQ4D used the largest printer in the world to complete the 1900 square feet project onsite for over eight days. Despite its size, SQ4D printed the house for less than $6000 in materials, with few labourers and a shorter construction period. The future printed houses are expected to decrease in the construction period by half due to ARCS enhancements implemented post-construction (Technologies. org 2020). ARCS is a patent-pending technology. Because of the benefits of robotically printing foundations, 3D printed walls, decorative walls, utility conduits, and other features, this digital technology can save up to 41% of total house costs. ARCS low-power consumption technology has provided solutions to traditional housebuilding problems by reducing the energy used to build houses and buildings, which positively impacts the environment. Furthermore, due to the shift from manual construction to robotics in construction, the number of workers, the proportion of human errors on the worksite, accidents, and waste of building materials have all decreased, reducing costs. This innovative technology can be considered a revelation in the construction industry because it can save costs by at least 30% while also making the house structure using mixed concrete safer, more robust, more fire-resistant, and performs better than traditional methods (Technologies. org 2020). According to the company, it uses ten gallons of fuel for every 500 square feet of the building, resulting in a 70% reduction in total building costs (Carolo 2020).

 (a)  (b)

Figure 6. (a) This large house took 48 hours to print, (b) the largest printer was used to build the house (Carolo 2020).

The following Table 1 summarized compares between the four selected 3Dprinted houses, which illustrates the evaluation of examples in terms of design, cost, time, quality, resource saving, performance, and sustainability. Each factor is measured in proportion to the project's achievement.

Table 1. Comparison between the 3D printed houses

	Prvok the floating house	**Curve appeal**	**The DFAB House**	**The biggest house**
Digital design	●	●	●	●
Reducing Cost	●	◙	◙	●
Savaging Time	●	●	◙	●
High Quality	◙	●	○	◙
Resources Saving	●	◙	◙	●
Performance	◙	●	●	●
Sustainability	◙	●	●	●
Symbol /Meaning: ●full achievement ◙partial achievement ○uncertain achieved ▬ not achieved				

3- Findings and discussion

3D printing is an important and promising technology, especially with Digital Transformation in Architecture and Construction. Some (encouraging) potentials of 3d printing have had significant influence and effects to enhance affordable and Sustainable Housing in the construction industry, moreover, high productivity and creativity via other design processes. The following paragraphs explain the selected findings of 3D printing potentials to get affordable and sustainable housing. As well, the most significant challenges could limit the adoption of 3D printing in the construction sector.

Analysis Model for 3D printing toward achieving the Sustainable Houses

SWOT analysis is a type of analysis method focused on the internal and external competition environment and competition conditions. It consists of four main factors (strengths, weaknesses, opportunities, and threats). By listing and comparing internal strengths and weaknesses to external opportunities and threats, it might get at a variety of conclusions (Renjie Ma 2013). Therefore, we developed an analysis model for 3D printed houses based on the characteristics of 3D printing technology in order to accomplish the Sustainable Houses base and benefit the 3D printing technology (Xiaodong Dong 2015; P. Rjan Alexandru 2013). The model consists of four sectors, as presented in table 2.

Table 2. SWOT breakdown of 3DP technology toward achieving the Sustainable Houses

STRENGTH	**WEAKNESS**
• Reduction in waste of building materials. • Condensed supply chain • Improved cost associated with labor • Easy market entry • Cost-free change of product design	• Materials are limited • Cost of entry and operating cost. • The limited size of the construction elements. • 3D printers could be large scale, therefore, difficult and costly to place on-site. • Lack of Control over Printers

• Creation of prototypes without tooling and getting quick feedback from the customers. • Reduction in the design-to-manufacturing cycle. • Eliminates the need of screwing and welding different parts of an end product. • Uses new, lighter, stronger and more durable materials. • Saving construction time • Cutting expenses • Improving efficiency • Enables more flexible designs (complex shapes and structures). • Eliminating tooling costs • Eliminating the waste that accrues in traditional manufacturing. • Environmental benefits from reduced transportation requirements. • Helps companies maintain and reinforce control of the entire value chain. • Increased flexibility in manufacturing	• Study the availability of equipment supply. • 3D printing incurs more up-front costs to create the digital model. • Need high technology skills, and experienced labor was needed to design and build 3D printed houses. • Suitable raw material is considerably more expensive than many raw materials used in traditional construction. • The cost of future materials • The speed of printing • The cost of 3D printers (industrial printers cost ranges from $95,370 to $15,000 - and home versions around $1,000). • At present, 3D printers can only make parts, not whole products unless the product is made 100% of the same material. • For thousands or millions of parts, injection molding is cheaper. • 75 percent of all patents in the field of 3D printing have been registered by a handful of countries: Japan, USA, Germany, Britain, South Korea, China. • Additive manufacturing is a slow process, requiring hours or days to finish the printed object.
OPPORTUNITIES	**THREATS**
• Building products can be customized • Encourages small production • Improved testing of products • New jobs are created • Experimentation is underway with printers capable of using multiple materials. • Manufacturing process is encouraged. • Increased innovation • Rising demand for designers, engineers and IT specialists.	• Copyright & ethics • Consumer rights • Job losses (traditional) • Knowledge gap, lack of familiarity in the industry with 3D printing technologies and applications. • Fear of change at governmental level • Governmental protection of the existing industries and companies. • Consumer regulations • Patents • Production control

• Printing infrastructure items on site for space programs (landing pads on Moon and Mars). • Producing complex parts in remote countries with lower input costs for electricity and labor. • Development of universal printing standards • Lower tooling costs • Growth in open-source files to print objects • Birth of a new industry supplying printing materials • Transportation cost savings • Supplying small production runs so entrepreneurs can scale up to mass-manufacturing without needing outside investment.	• Potential that any innovation can be instantly copied. • Brand and product quality • The impact of certain materials on human health and the environment, especially with nanomaterials. • Uncontrolled or unregulated production of body parts, medical equipment or food.

Source: Authors` editing from: Cohen et al. (2014); The Economist (2012, 2015); World Economic Forum (2015); D`Aveni (2015); McAlister C and Wood J 2014.

The sustainable solution for the Traditional Constructed Houses

Table 3 compares the 3D printed house to a traditional constructed house based on the study parameters. Considering the variables, 3D printing achieves a higher overall performance, which is dependent on the availability and maturity of its process with reputable 3D printer companies, and it increases the market potential for 3D printing industrials. Additionally, it is critical to demonstrate that 3D printing as a new technology will offer a wide range of opportunities and prospective market space, which should mitigate its current weaknesses and threats.

Table 3. Comparative Analysis between 3D Printed Constructed House and Traditional Constructed House

Category	**3D Printed House**	**Traditional Constructed House**
Design Concept	The 3D digital object (drawing or scanning)	The 2D drawing
Design Method	Digital File - CAD Software - 3d Model BIM File - File Converted To STL File	Traditional Files & documentation using - CAD Software
Construction Method	Printing method (FDM, SLA, SLS, inkjet bio printing, Extrusion bio printing, ...)	Traditional housebuilding
Materials	Advanced materials	Traditional Materials

	Thermoplastics, ceramics, metals, paper, food, polymers, nanomaterial and biomaterials	(Concert, sand, metals, cement,…).
Related Equipment	Robotics	Traditional equipment
House Size	Limited but accurate size	Multiple size but not accurate
Productivity	Boost productivity	Reduce productivity
Equipment Cost	High Cost	Low Cost
Reducing Cost	Low Cost	High cost of construction
Project Duration	Shorter build time	Longer build time
Quality	Improve the quality	Poor quality
Safety	Reduce (safety, health, etc.) issues	Suffer from (safety, health, etc.) issues
Resources Saving	Save Resources	Waste Resources
Finishes	Better finishes	Poor finishes
Coordination	Integrate between supply and demand	Gap between supply and demand
Sustainability	Build sustainable housing by reducing - The energy - The impact on the environment - Human errors - Cement usage. - CO2 emissions.	Traditional housebuilding increases - The use of energy - The impact on the environment. - Human errors. - Cement usage. - CO2 emissions.

In compared to the traditional method of house construction, the 3DP technique is a more sustainable method of house construction (Russell P 2015). According to (Yingchuang Shanghai 2018), 3DP consumed just 40% of the raw resources required to construct a house using the traditional method. Additionally, (Yingchuang Shanghai 2018) reported that 3DP reduces the energy necessary to construct structures by 30% to 70%. Safety enhancements and labour reductions are critical components of achieving sustainability in building construction.

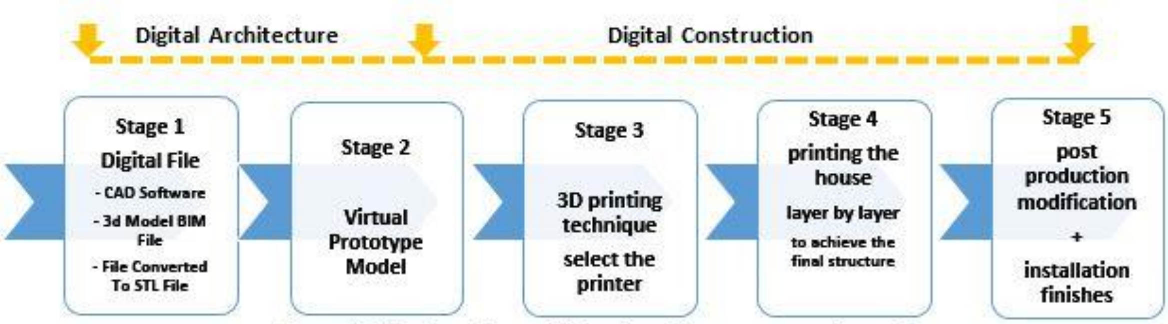

Figure 7. The flowchart of 3D printed house process by author

Achievement of Sustainability

This prominent factor is critical and vital to evaluate the 3Dp influence on sustainability performance in improving energy efficiency and emission reduction in construction projects (El Mogy T 2021). Accordingly, it is vital to analyse how sustainable the 3D printed houses are, not only environmentally but also economically and socially, as shown in table 2. One of the most significant advantages in sustainability aspects is that houses can be built with raw soil or natural resources taken straight from the site (Ramadany M, & Bajjou M S. 2021). Also, it can be built in curved and complex shapes, as shown in, enhancing the house's environmental performance such as thermal comfort and energy efficiency, which is completely in line with sustainable development principles. (Mahadevan 2020). Moreover, the 3D printing technique will depend on the materials life cycle and help achieve better time and cost management, enable lean construction, and promote sustainability in the building sector (Tartarini 2020). In addition, from the point of financial view, 3Dp could significantly reduce overall house costs. Various opportunities in 3d printed housing are significant in the whole life cycle. That will help 3Dp to take place in practical applications and market (Marchesi M, & Tweed C. 2021). The transformation to automation will replace labour and reduce manual jobs, not only in the construction industry but even office staff could be replaced by artificial intelligence (AI) and robots. Safety and health issues are other aspects. For 3D printing advances, these are vital to assisting the onsite environment through providing more safety and security procedures.

Increased the construction performance

As shown in Fig. 8, 3DP can generally save project resources and save costs. In addition, the status of the 3DP potential to reduce the overall construction costs had evaluated. The ability of 3Dp to print curvet and organic structures, facades, and roofs reduce execution time and errors from implementing complex designs more than traditional construction methods, lowering costs. Also, experts who continuously develop and improve materials, software, and robotics have increased construction efficiency and affordability (Arleo L 2021). For instance, the 3D printed houses in previous projects listed the benefits of reducing construction period, labour, and materials. We cannot ignore the high cost of the required equipment and machines on-site that can affect and change the project costs, which need more investigation in the future.

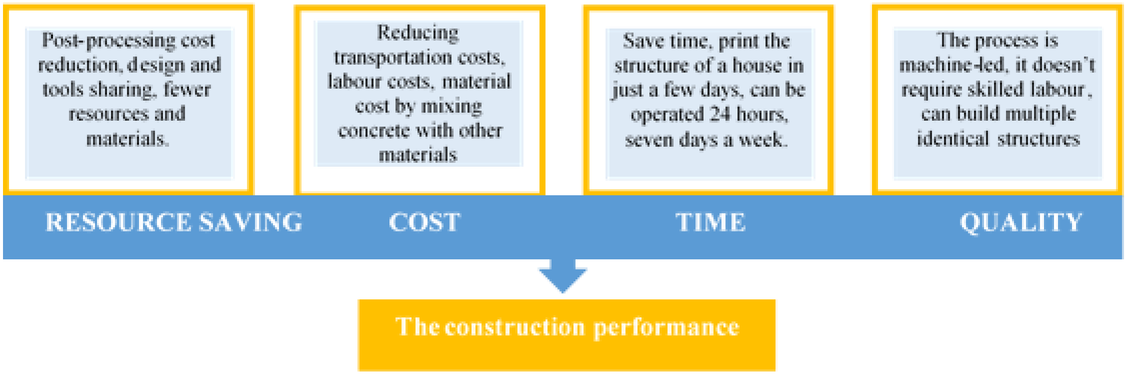

Figure 8. The top benefits of 3D printing effect on the construction performance by the author

Developed materials

Building and construction are still the most considerably consumed industrial sectors of raw materials and energy, such as concrete and bricks. Fig. 12 shows the most widely used materials for 3D printers. Plastic is the most commonly used, followed by resins, metals, multicolour, composites, and ceramics (Yap Y L, 2020). According to Mahadevan M, Francis A, and Thomas A. (2020), the improvement of materials used for 3D printing to address sustainability concerns associated with its use in construction. The performance of 3D printable concrete as the building envelope is the lowest in this criteria, in comparison to other materials, necessitating further experimental studies in this domain (Mahadevan 2021).

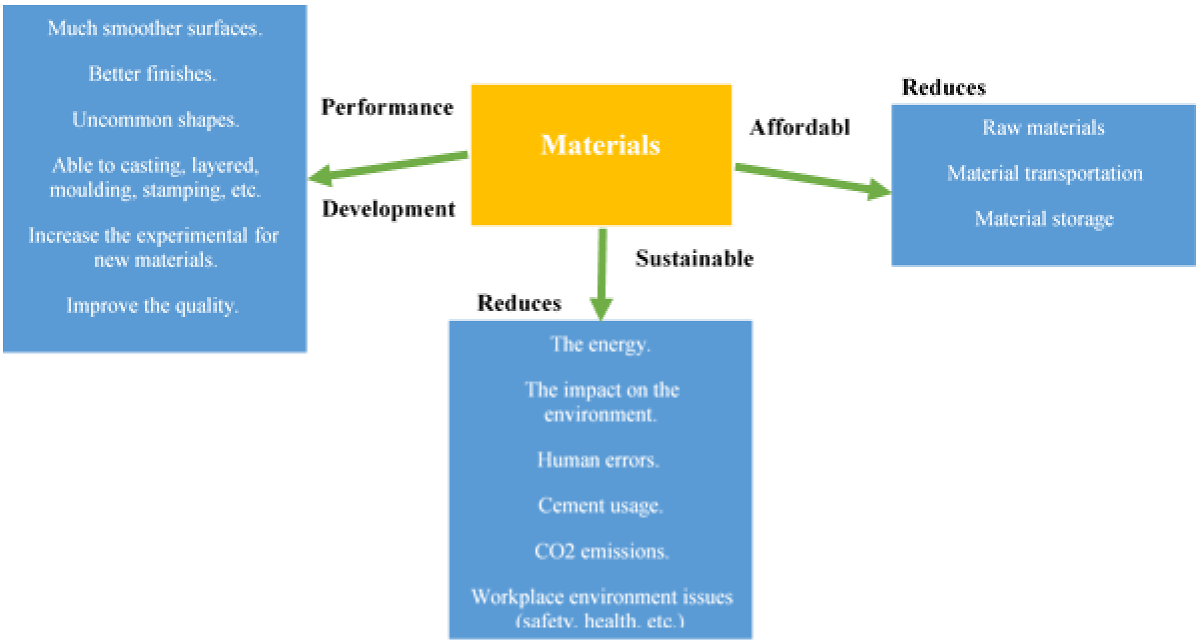

Figure 9. The relationship between developed materials, sustainability, and affordability due to 3D printing adoption by the author

3D printing is an additive layer by layer process, through the 3D printer, to add a layer above a layer with a specific thickness until the surface to be printed is formed (Schuldt S J 2021; Bhatia A 2021). Referring to The State of 3D Printing report, 2020, each layer varies in thickness from 0.3 mm to 0.06 mm according to the specific process, resulting in high-quality surfaces, which are particularly easy to be formed for curved surfaces and walls. Materials science is constantly undergoing studies and experiments from the university and scientific institutes with a vision of developing materials used in 3D printing technology, whether through improved environmental, economic and social performance or the ability to mould, layer and shape. Fig. 9 presents the relationship between developed materials, sustainability, and affordability through 3D printing adoption.

3d printing Houses limitations and challenges

Despite the numerous and promising potentials and advantages of 3Dp technology in digital architecture, construction, and materials science, its role in improving the performance of 3D printed houses in terms of sustainability, affordability and materials development. 3Dp technology is still at the beginning of the path. Some of the challenges that need to be taken into account in the construction industry that could negatively impact the adoption of 3D printing technology (Hecker S, 2021).

Conclusion

Advances in 3D printing and digital design techniques have made valuable contributions to digital architecture, building and construction, and sustainable housing, and materials science. The possibility of improving the current state of building and construction sector, particularly in developing countries, has limited resources that must be used efficiently, quickly, and cleanly. Moreover, with a high degree of accuracy and discipline, it allows for complete control of the construction process from design, implementation, operation, used materials, quality of labour, site condition, and other important factors and influences the construction process stages. Therefore, it is vital to apply and exploit new technologies, which provide more sustainable, resource-saving, and environmentally friendly solutions to rebalance the built environment. Indeed, we need to allow this technology to discover all its potential and challenges to open up development and innovation in architecture, construction, manufacturing, scientific research, etc. The 3D printed houses approach is based on techniques such as BIM that allow the easy study of the impact of the building, economically and socially, as a result of obtaining the building as a 3D model with information and features that can easily be analysed and used in other processes. Guarantee a rapid and more effective building process. Efficiency in the techniques and tools used in the construction process using 3D printing is necessary to determine the quality of the building and practical solutions to complex problems and produce exclusive use of the benefits offered by 3D printing technology. Knowledge, expertise, training, availability, and integration of technology, software, and tools are essential factors at all stages. Efficient and scientific expertise in digital architecture and construction techniques. Which has to impede their use in AEC. With the increasing implementation of this technique, it is possible to detect other aspects that have a negative or positive impact on the construction process, such as improving the performance of the digital design process. In addition, there has been considerable development in the field of materials science from different disciplines to obtain energy-saving, environmentally friendly, and more sustainable materials. The novel 3Dp technology requires additional studies and research for 3D printing applications and focuses more on digital design, digital architecture, and construction practices. In the field of Architecture, 3Dp is still in the initial conceptual phase. The paper proposes research interests, challenges, and future topics. For example, the enormous digital design potentials, software, applications, digital materials, equipment, tools, and digital skills will urgently need to integrate all digital technologies to increase potentials and reduce threats, especially with digitalization.

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