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APPLYING 3D PRINTING TECHNOLOGY IN CONSTRUCTING SUSTAINABLE HOUSES

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APPLYING 3D PRINTING TECHNOLOGY IN CONSTRUCTING SUSTAINABLE HOUSES

Abstract

Innovation is advancing at an ever-expanding pace and has been for decades. Regular objects have gotten to be minimal in measure and cheaper to deliver. 3D printing technology (3DP), also known as additive manufacturing (AM), has gaining rapid development in recent years. is a method for turning a computer file into 3D solid objects of any shape or geometry. The creation is accomplished by building up layers of a certain substance until the full item is produced. The 3D printing technologies, comparing to traditional techniques of constructing the buildings, could be considered as environmentally friendly derivative giving almost unlimited possibilities for geometric complexity realizations. The primary issue is that the building sector has a significant negative influence on the environment. Some modern technologies are being applied to reduce materials usage and carbon emissions like 3D printing. The major purpose of this article is to compare between conventional approaches and 3D printing technology to assess their effects on sustainable housing, evaluate how 3D printing functions and consider its advantages and disadvantages. To conduct the research, a comparison between traditional techniques and 3d printing technology will take place to see their impacts on sustainable houses, theoretical studies will be done on both :3D printing concepts and application in architecture and its effectiveness on environment and sustainability. In addition to the practical studies, experimental ones where case studies are selected according to the inductive method mentioning the selection criteria. Three case studies will be analysed, where the 3D printing technology is achieved, TECLA, a circular housing prototype in Ravenna, Italy, the Dubai municipality and Beckum First 3D Printed house in Germany.

Keywords

3D Printing, Building Technology, Sustainable Housing, Robots, Materials

1. INTRODUCTION

Three-dimensional (3D) printing or sometimes known as additive manufacturing is an advances manufacturing technology that allows complicated form geometries to be manufactured automatically from a computer-aided 3 model without any of the tool and set-up costs usually associated with manufacturing, and this is achieved using additive processes, as shown in figure 1. (An item is built in an additive technique by laying down successive layers of material until the product is complete) (Gibson et al, 2010). Due to the considerable benefits of developing working prototypes in an acceptable build time with less human interaction and less material waste, as well as the ability to generate complex forms with optimum structural qualities through 3D modelling and then its fabrication with the use of machines and robots, this automated manufacturing approach has been used to many various domains of industry today such as aerospace, automobile, and medical. (Tay, 2017).

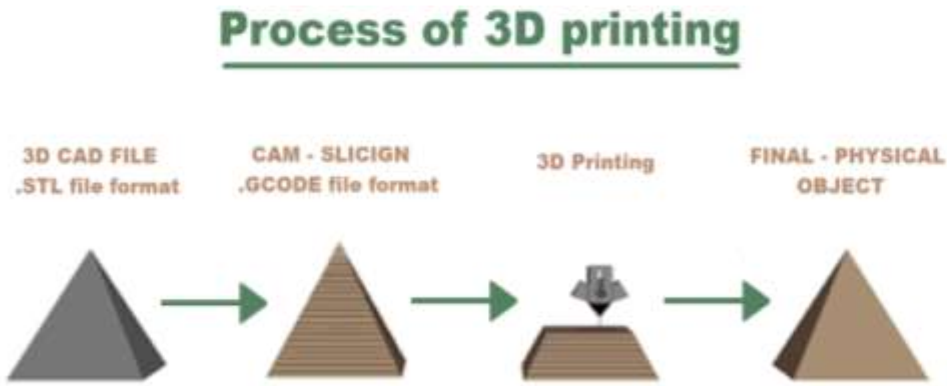

Fig.1: Process of 3D printing
Source: https://www.theengineeringprojects.com

The first 3D printer was introducing in 1984. 3D printing has become one of the fastest growing technologies, it was once an extremely difficult and, moreover, costly technology. Over time, 3D printing became more prevalent in everyday life, with printers being employed in a wide range of industries, as shown in figures 2 and 3. Many firms from many industries throughout the world have set their sights on improving printing materials and 3D technologies. Recently, a true revolution in the construction business began when the first home was printed, ushering in a new era in construction technology. The application of this technology to the built environment, appears to improve our standard construction tactics while minimizing the need for human resources, large capital investments, and extra formworks. (Drdlová, 2016).

Fig.2: 3D printing
Source: https://www.idtechex.com/fr/webinar/3d-printing-composites

Fig.3: 3D printing in Architecture
Source: https://www.archdaily.com/970937/can-3d-printing-reshape-residential-architecture

In order for a subsequent conversation to proceed with comprehensive knowledge of its meaning, the term "sustainability" in the context of architecture must be defined. Sustainability is a design strategy that is more than just energy efficient; to create a sustainable building, all of the resources that go into it must be taken into account, including materials, fuels, and an understanding of the demands of the users. According to the World Commission on Environment and Development, "sustainability is economic development that fulfills current demands without jeopardizing future generations' ability to satisfy their own needs." (WCED, 1987), but it’s been a while now and the development of mankind been on the expanse of mother nature, the construction industry for example has been recognized as one industry that consumes considerable number of resources and poses significant environmental stresses. Therefore, the search to find cheaper and more sustainable construction techniques has begun. 3D printing or Digital architecture are one of these alternatives. “Buildings consumed 36% of the total energy used, 30% of the raw materials used and 12% of potable water consumed in the US” (Klotz, 2016). Construction innovation studies have been done in two ways during the last few decades to solve productivity, environmental, and other challenges. One type of construction innovation responds to external needs (such as the wants of clients), whereas the other type comes from other industries. However, in the construction business, the primary focus of innovation strategy is to use technology from other industries to supplement existing competitive advantages. One of the reasons for the construction sector's reputation as a low-tech, low-innovation business is because of this. (Tidd et al., 1997). In the building sector, there have been numerous attempts to employ 3-D printing to boost customization, shorten construction time, and improve pricing. Major contractors, for example, have a suite of modeling tools and a 3-D printing method to print 3-D architectural models (such as Foster and Partners in London, UK).

1.1 Research Problem

The main problem is that the construction industry contributes to many environmental impacts. According to the World Watch Institute the construction sector contributes to 23% of air pollution, 40% of drinking water pollution, and 50% of landfill wastes. These numbers are alarming. Some modern technologies are being applied to reduce materials usage and carbon emissions like 3D printing. The building industry has long been regarded as a resource-intensive business that puts major environmental strains on the environment. Buildings consumed 40% of the total energy used, 50% of the raw materials used and 12% of potable water, produce 30% of CO2 emissions and 30% of waste. (UNEP, 2009).

As indicated in figures 4 and 5, the environmental impact of Conventional Concrete Process CCP: (a) CO2 emission; (b) embodied energy. The use of Conventional Concrete Process (CCP), produce waste more seven tons comparing to Contour Crafting technique (CC) that use the material needed only. CO2 emission from the CC process is small fraction compared to the current emission of the conventional concrete process (CCP) of the concrete masonry unit. (Le, T.T., et al, 2017).

Fig.4: Buildings consumption and production

Source: https://www.resourcepanel.org/reports/assessing-global-resource-use

Estimate of global resources used in buildings [1]

Resource	(%)
Energy	45–50
Water	50
Materials for buildings and roads (by bulk)	60
Agricultural land loss to buildings	80
Timber products for construction	60 (90% of hardwoods)
Coral reef destruction	50 (indirect)
Rainforest destruction	25 (indirect)

Estimate of global pollution that can be attributed to buildings [2]

Pollution	(%)
Air quality (cities)	23
Climate change gases	50
Drinking water pollution	40
Landfill waste	50
Ozone depletion	50

Fig.5: Building consumption of global resources and estimate global pollution.

Source: https://www.resourcepanel.org/reports/assessing-global-resource-use

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1.2 The Aim of the Study

The main aim of this paper is to **“Compare between traditional techniques and 3D printing technology to see their impacts on sustainable house, interpret of the 3D printing works and analyze both its advantages and disadvantages”.** Many new experiments in the construction sector have been undertaken to fully investigate the potential of 3D printing in the construction business. These experiments, however, are disjointed. As a result, a critical examination of the history and current state of 3D printing in the construction industry is required.

2. LITERATURE REVIEW

The paper presents a theoretical background for the 3D Printing Technology and its use in architecture and in the sustainable housing.

2.1 Definition of 3D Printing technology or Additive manufacturing

Building technology based on 3D printing is a new construction process that began with the introduction of the 3D printer. 3D printing, also known as additive manufacturing, is an automated method that creates complicated shape geometries layer by layer, through a sequence of cross-sectional slices, from a 3D model (computer-aided design (CAD) model). The technology has been used in the industrial industry for decades and is now being used to print houses and villas in the construction industry. "3D printing is an additive manufacturing technology in which objects are built layer by layer using a series of cross-sectional slices." (Berman, 2012).

2.2 Definition of ‘Sustainable House’

The goal of sustainable construction is to meet current infrastructural, housing, and working environment needs without jeopardizing future generations' ability to meet their own needs. This entails ensuring that resources are utilized efficiently to benefit society and the globe as a whole. (UNEP, 2009). In the housing sector, the term "sustainable housing" refers to a process that involves less waste, more re-use, and recycling, as well as lower life-cycle environmental impacts and costs, higher durability, less maintenance, and more user satisfaction. Sustainable dwellings should be constructed with materials that have a low environmental impact. Local produce or recycled materials, for example, could be used. Sustainable home design emphasizes environmental protection, energy efficiency, and a number of other supporting issues (Almssad, 2022).

There are three main components of a sustainable home:

- **Long-term environmental stability**
  During construction and over the life of the house, the house is designed to reduce carbon emissions, conserve water and energy, and reduce waste.
- **Universal design / social sustainability**
  The house is created with built-in safety mechanisms to keep people safe. It incorporates security features that help to reduce crime and provide residents a better sense of security. Children and people with restricted mobility, for example, benefit from features that enable flexibility and comfort for people of various abilities and stages of life.
- **Long-term economic stability**
  The house is built to save money both during construction and over its lifetime. Careful planning eliminates the need for large future modifications and lowers energy, water, and maintenance expenses.

2.3 3D Printing of Buildings for Construction of the Sustainable Houses

The usage of 3D printing technology in construction will improve sustainability. Houses can be constructed using the material life cycle, which can be used to assess the environmental sustainability of various building materials. Creating buildings with complex shapes could be one of the most advantageous aspects for most architects. Their creativity will be able to overcome prior limitations imposed by traditional construction processes. Although 3D printing has the potential to alter today's architecture, it must be developed with sustainability in mind, both in terms of material selection and building approach. (Kim, et al, 2020).

As a result of its ability to give significant environmental, social as well as economic benefits, the use of 3D printing for construction project delivery is believed to be the way forward in the quest for sustainable construction projects housing inclusive (Sakin and Kiroglu, 2017). To improve the use of 3D printing for sustainable low-income housing delivery, several factors - indicated in figure 6 - can be considered, the most important criteria customers consider when choosing a 3D printer is the size, affordability, friendly use of technology without the need for advanced training, quality of products printed and time frames in which products are printed. (Pîrjan and Petroşanu, 2013).

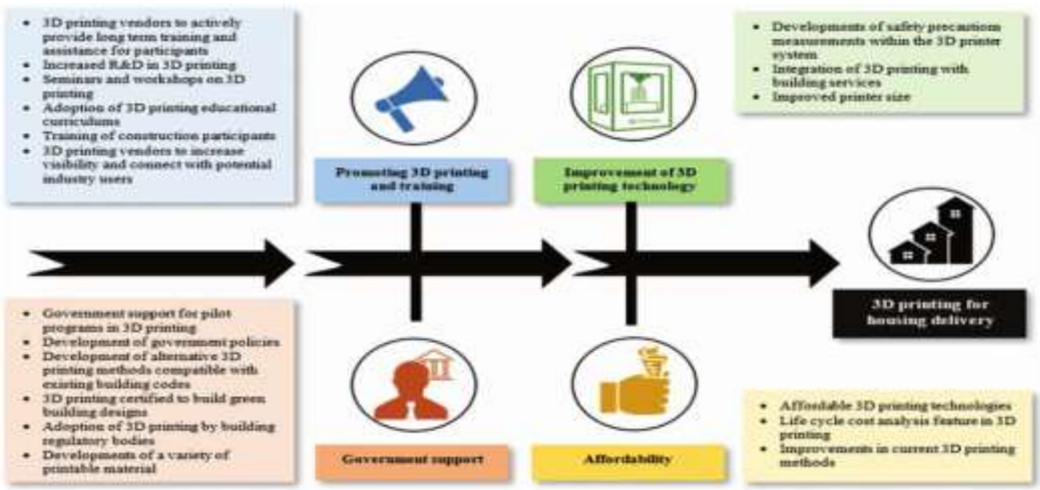

Fig.6: Measures for improving the adoption of 3D printing for sustainable housing delivery.
Source: 3D printing for sustainable low-income housing / Article in Journal of Green Building · March 2021

2.4 Historical Background of the 3D Printing Technology

The 3D printing technology was experienced in Mexico and Africa to building small houses' experiments, as shown in figures 7 and 8. The historical background of 3D Printing is divided to 3 parts:

2.4.1 3D printing and construction parts

Until recently, 3-D printing was only used in the manufacturing industry. It was used to make prototypes with small part sizes, limited production volumes, and complicated designs. As a result, rapid prototyping (RP) technology was commonly used at the time to refer to 3-D printing technology. (Gibson et al, 2010). Charles Hull invented the first 3-D printer in 1986, utilizing stereo lithography technology. Other RP technologies were put onto the market in the following years. SLS and FDM, for example, were both launched to the market in 1989. RP technologies were employed to create prototypes for goods mostly utilized in the industrial industry at this time. (Arthur et al., 1996).

Fig.7: 3D printed house in Mexico.
Source: https://www.3dnatives.com/en/3d-printed-houses-market-250220204/#!

Fig.8: First 3D printed house in Africa.
Source: https://www.3dnatives.com/en/3d-printed-houses-market-250220204/#!

2.4.2 3D printing and architectural model

The construction industry has employed 3-D printing to produce architectural models since the 2000s. It has been investigated how stable different 3-D printing techniques are for producing architectural models. Gibson et al., for instance, built architectural models that were both geometrically simple and sophisticated using RP approaches. SLS has proven to be capable of creating robust models, whereas FDM printing led to the collapse of one architectural model. The printing procedure might be completed in a few hours. There were several 3-D printing processes that could be applied to construct architectural models depending on the amount of precision necessary (Gibson et al., 2002).

2.4.3 3D printing and entire building projects

It was stated that due to the size of 3-D printers, medium or largescale models or structures would not be able to be manufactured utilizing 3-D printing technology. However, in recent years, there has been substantial progress in building large-scale 3-D printers to address the need for industrial-scale 3-D printing. Three big advancements in the use of 3-D printing to create whole construction projects were made. In 2014, WinSun, a Chinese architecture firm, successfully printed a set of residences in Shanghai (each 200 m2) in less than a day. The 3-D printer created one home (about 1100 m2) and one five-story apartment complex in 2015. The villa and apartment were not printed together as a single unit. Instead, most of the building components were printed and transported to the construction site for installation (Masoud, Rafea, 2019).

2.4.4 Birth Of 3d Printing:1980

Although the notion of 3D printing was initially suggested in the 1970s, it was not until the early 1980s that the first tests on the subject began. Dr. Kodama, who invented a quick prototyping technology, took the first baby steps toward the printing revolution. He was the first to explain a layer-by-layer technique for producing and manufacturing the predecessor of Stereo lithography, often known as SLA (Campbell, 2011).

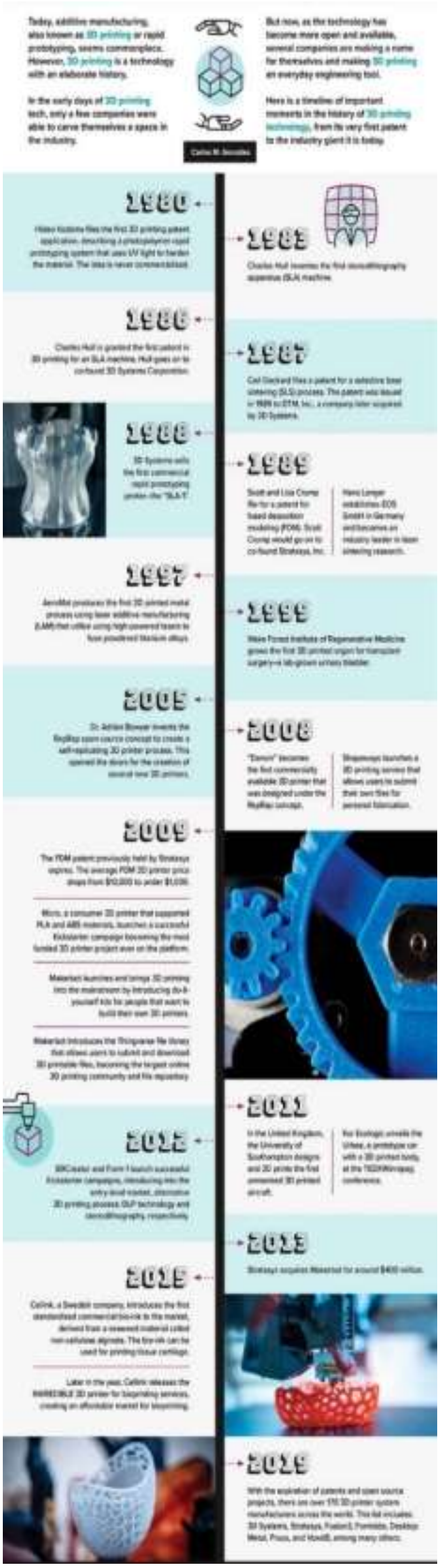

Fig.9: 3D Printing Evolution TimeLine Source: https://www.asme.org/topics-resources/content/infographic-the-history-of-3d-printing

While SLA was being commercialized, Carl Deckard of the University of Texas submitted SLS (Selective Laser Sintering) technology for its first patent for 3D printing technology. The powder grains were formally merged using a laser in this way. Scott Crump, one of the co-founders of Stratasys Inc., went ahead and filed a patent for FDM (Fused Deposition Modeling). Three separate types of 3D printing technology were patented within 10 years of each other, giving rise to 3D printing.

Figure 9 glimpses the evolution timeline of 3D printing technology in industry, while figures 10 and 11 compares between the printing in history and 3D printing nowadays.

Figs.10 and 11: History of printing vs. 3D printers nowadays
Source: Excell, Jon (23 May 2010). "The rise of additive manufacturing". *The Engineer*. Retrieved 11/9/20

2.5 Types of 3D printing

The different types of 3D printing are:

2.5.1 Contour Crafting

As shown in figure 12, contour crafting is a 3D printing process that permits architectural-scale structures to be created. By far the most well-known and investigated type of digital manufacturing is concrete extrusion, which was pioneered by Berokh Khoshnevis as Contour Crafting and most recently evaluated by Buswell et al. While working on a machine that could build buildings, he devised the Contour crafting technique. A pump delivers fresh material to a nozzle, which is digitally controlled to transport the material to the correct area (Khoshnevis, 2004).

To position the nozzles, a moving robotic arm - shown in figure 13, a huge gantry system, or a delta printer system can all be utilized, but they all require a printer that is larger than the component to be produced.

Fig.12: Contour Crafting
Source: https://www.sculpteo.com/blog/2018/06/27/3d-printing-for-construction-what-is-contour-crafting

Fig.13: Schema of built walls by CC and placing the passages for the needed installations.
Source: https://www.semanticscholar.org/paper/Automatic-Construction-by-Contour-Crafting-Khorramshahi-Mokhtari

Despite the fact that shape flexibility has greatly increased, several challenges remain, particularly in terms of structural reinforcement, dimensional stability, and tolerance. The reinforcing problem has been overcome in the past by post-tensioning or putting passive reinforcement in gaps and filling them with concrete, thereby turning the print into a lost formwork (Martin, 2016).

2.5.2 Selective Laser Sintering and Selective heating Sintering

SLS (selective laser sintering) is a layer manufacturing technique that allows complicated 3-D things to be created by stacking successive layers of powder material on top of one another. A concentrated laser beam is employed in SLS to carry out the consolidation process. As referred in figure 14, SLS is commonly referred to as selective laser melting (SLM) or direct metal laser sintering when it is used to make metal items (DMLS). The metal particles are fully melted by the laser beam in the SLM process, for example. As a result, the printed objects have a substantially greater density than SLS-produced products (Kruth, 2005).

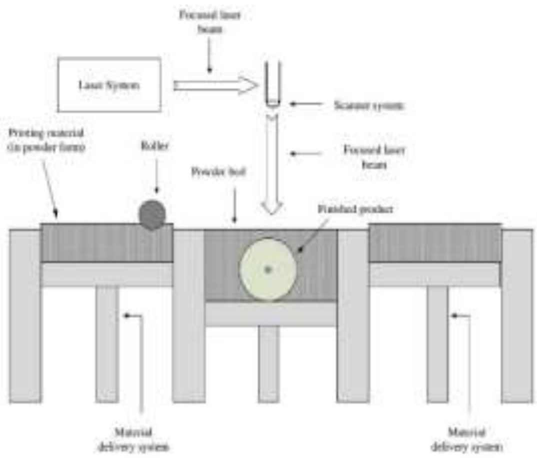

Fig.14: Components and processes in SLS
Source: Peng Wu, 2016, "A critical review of the use of 3-D printing in the construction industry"

2.5.3 Shape Forming Support

Another way for constructing digitally generated buildings is to employ flexible formworks to create a shape in space. As shown in figure 15, this may be done in a prefabrication environment, as ETH Zurich researchers recently demonstrated using the Knitcrete technique (Popescu, 2018). In the first situation, a flexible framework is molded and concrete is cast into the mold, but in the second scenario, a knitted textile is tensioned in space to form a shape that is then concreted via layering (Schipper, 2015).

Fig.15: KnitCandela - A flexibly formed, thin concrete shell at MUAC, Mexico City
Source: RocketshipWP, 2018

2.5.4 Cellular Fabrication

Cellular Fabrication is a 3D Printing for Composite Construction, where a composite is just a collection of components that come together to form a whole that is more than the sum of its parts. These components come together to create habitable enclosures. 3D-printed construction should follow the same logic to perform as well as or better than traditionally made buildings (Clinton, 2018).

Fig.16: Outdoor structure in Nashville
Source: Clinton, 2018

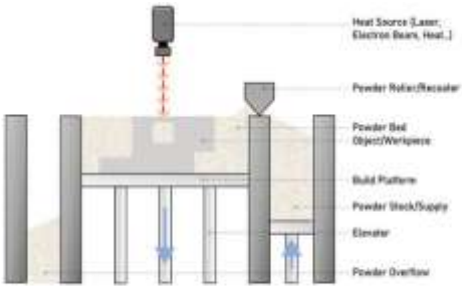

Fig.17: PBF-based 3D printers' functional diagram
Source: Peng Wu, 2016, “A critical review of the use of 3-D printing in the construction industry”

A 3D printing material that meets all the parameters and performance expectations we have for the structures in which we live, work, and play. As a result, cellular fabrication is built to combine and contain numerous materials that enhance the functionality of 3D printed geometry.

In Nashville, a project is an outdoor band shell, shown in figure 16. It uses cellular 3D printing techniques, in which material is solidified in midair to build open matrix structures that may take on nearly any shape. This project involves employing these techniques to produce a 42-foot-diameter band shell that stands more than 19 feet tall, making it North America's largest free-form, 3D-printed structure (Clinton, 2018).

Table 1: Characteristics of 3-D printing technologies

3-D printing technologies	Components	The printing process	Cost index[1]	Printing time index[2]	Smallest feature[3] (μm)	Printing materials
Stereolithography	• A perforated platform • A container of a liquid UV-curable polymer • A UV laser	Using a bean of UV laser to harden the liquid polymer and lower the platform to create multiple layers.	200–400	100–120	1–366	Liquid photosensitive resins
Fused deposition modeling	• A printer head • Printing material • Support material	Printing material is fed to the printer head to deposit the material to the layers.	100	100	260–700	Acrylonitrile butadiene styrene (ABS); Elastomer; Wax; Metal
Inkjet powder printing	• A printer head • Printing material in the powder form • Binder • An oven	Printing material in the powder form is deposited. Binder is then sprayed, heated and dried. The product will be cured in an oven when completed.	40–80	20	350–500	Polymers; metal
Selective laser sintering and selective heating sintering	• Focused laser beam • Printing material in the powder form	Printing material in the poser form is deposited. It is then consolidated using a focused laser beam. The process is repeated from layer to layer.	200–400	100–120	45–100	Nylon based materials; rapid steel; sand form
Contour crafting	• A gantry system • A nozzle • Printing material • Trowels	Printing material is extruded from the nozzle and then troweled. The gantry system is computer controlled and moves with the nozzle.	N/A	4 mins/m^2	N/A	Ceramics materials; concrete

Source: Peng Wu, 2016, “A critical review of the use of 3-D printing in the construction industry”

The components, printing processes, and some general characteristics of several 3D printing technologies are summarized in Table 1. As shown in Table 1, the cost, printing time, precision, and available materials all influence the choice of appropriate 3-D printing method.

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2.6 Advantages & Disadvantages of 3D Printing of Sustainable Houses

When compared to typical manufacturing methods, this technology offers a number of advantages. Design, time, and money are just a few of the benefits. Buildings made with 3D printing technology will be more sustainable. The material life cycle, which can be used to assess the environmental sustainability of building materials, can be used to construct houses. One of the most significant advantages for most architects may be the ability to design buildings with intricate shapes. Their creativity will be able to overcome prior limitations imposed by traditional construction processes. Although 3D printing has the potential to alter today's architecture, it must be developed with sustainability in mind, both in terms of material selection and in terms of the manufacturing process (Gowrishankar, 2018). The benefits of advancing 3D technology in building are numerous, with the following being the most important:

- **Lower costs** – printing construction elements for houses is much less expensive than traditional construction methods, and material transportation and storage on construction sites is limited.
- **Environmentally friendly** construction methods and the use of low-embodied-energy raw materials (e.g., construction and industrial wastes);
- On-site injuries and deaths will be reduced because printers will be able to perform most hazardous and dangerous tasks.
- In comparison to traditional methods, wet construction processes are minimized, resulting in fewer material wastes and dust.
- **Time savings** – the time it takes to finish the building can be significantly reduced.
- **Minimizing Waste** – When compared to alternative methods that cut large chunks of non-recyclable materials, part production requires only the materials needed for the part itself, with little or no waste.
- **Flexible Design** – Unlike traditional manufacturing processes, 3D printing allows for the design and printing of more complex designs. Traditional technologies impose design constraints that are no longer applicable when 3D printing is used. Figure 18 glimpses a hint about this comparison.

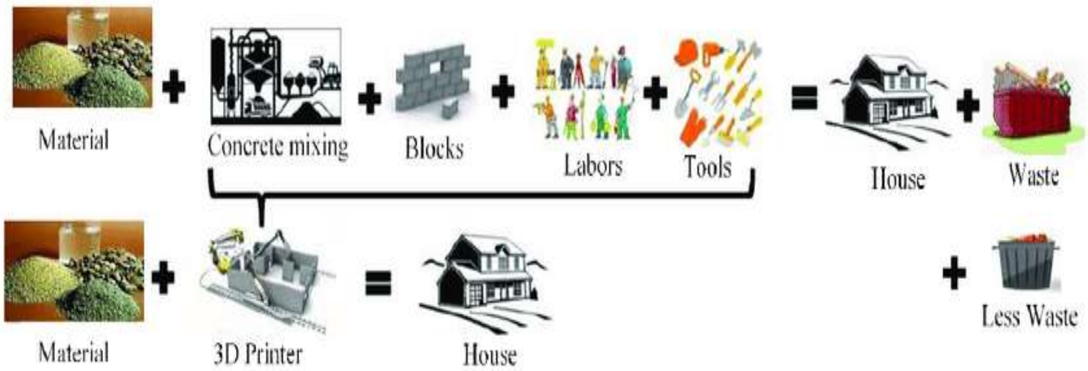


Fig.18: Conventional construction vs 3D printing construction process

Source: Allouzi, R.; Al-Azhari, W.; Allouzi, R. Conventional Construction and 3D Printing: A Comparison Study on Material Cost in Jordan. J. Eng. 2020

Meanwhile, the challenges facing the construction industry today are:

a. It is still a limited and expensive technology.
b. The industry is not familiar with this technology.
c. 3D printers for construction such as concrete structures can be large and can be costly to transport to the site.

The 3D Printing technology applied to construction sustainable houses meet more than one sustainable development goal – referred to in figure 19, it meets:

SDG 1: No poverty / Affordable houses
SDG7: Affordable energy
SDG 9: Industry innovation
SDG 11: Sustainable cities
SDG 12: Responsible consumption and production / Reduce waste production
SDG 13: Climate action

Fig.19: Sustainable Development Goals
Source: https://sdg-tracker.org/

2.7 Analysing Similar Examples

This part presents two different examples about the topic.

2.7.1 Example 1: 3D Printed house in Russia

This project is considered the world’s first Incredibly Cheap House in Stupino, Russia

Location: Stupino, Russia

Architect: Apis Cor, and Russian real estate developer PIK Project Erection time: 2017

Area: 40m2

As shown in figure 20, this house was 3D printed in just 24 hours. The basic elements of the house, such as the walls, partitions, and building envelope, were all printed totally out of a concrete mixture. The total cost of construction for the house is $10,134. One of Apis Cor's Russian facilities houses the home, which has a corridor, bathroom, living room, and kitchen. The mission was completed with the help of a mobile 3D building printer, and the residential structure's unique design "was chosen expressly, since one of the major goals of this construction is to demonstrate the flexibility of equipment and diversity of accessible forms," according to the researchers. In an additive technique, different layers of concrete are precisely laid over one another to form the building's walls.

Fig. 20: 3D printed livable house in Russia
Source: https://www.boredpanda.com/

As shown in figures 21 and 22, the printing method is versatile enough to accommodate a variety of installations and fittings while also conforming to the appropriate shapes. The "ink" for the 3D printer was a concrete mixture that serves as the house's main structure. This is capped off with a roof system that can endure severe snowfall, and both solid and liquid insulation layers work together to keep the house at a comfortable temperature. Because the printer creates self-bearing walls and partitions, it saves up to 70% on erecting building boxes as compared to traditional construction processes like the block method, which requires each block to be placed, cut to size, and aligned. It's also necessary to transport the necessary equipment and tools to the construction site, replace them when they break, unload materials, and supervise the builders. Human error is frequently present, and a conventional cottage house might take up to two months to complete.

Fig.21: Texture view of a 3D printed wall.
Source: https://www.boredpanda.com/

Fig.22: Machinery used in building
Source: https://www.boredpanda.com/

2.7.2 Example 2: 3D Printed house in Netherlands

In the Netherlands, a boulder-shaped concrete house has become the country's first 3D-printed dwelling.

Location: Eindhoven, Netherlands

Architect: Architects Houben & Van Mierlo

Project Erection time: April,2021

Area: 94m2

Fig.23: 3D printed livable house exterior view.
Source:
https://www.designboom.com/architecture/project-milestone-first-3d-printed-concrete-house

As shown in figure 23, the single-story home was built as part of Project Milestone, a five-home 3D printing program in Eindhoven, and is touted to be Europe's first 3D-printed home where people reside. Each house in this project is a two-bedroom single-story single-family residence with a total area of 94 square meters. The house is made up of 24 massive concrete parts that were printed in a local factory in 120 hours before being constructed on site.

Fig.24: 3D printing on site work
Source:
https://www.designboom.com/architecture/project-milestone-first-3d-printed-concrete-house

According to the architects, the house is fashioned like a rock to blend in with its woodland surroundings in Eindhoven's Meerhoven neighborhood. The dwelling is currently occupied by a Dutch retired couple and is Europe's first legally habitable 3d-printed house. The home's piled concrete walls were left exposed on the inside to show off its layered texture. Floor-to-ceiling windows are sunken into the thick walls, interrupting the concrete layers. The 94-square-metre residence features an open-plan kitchen-diner and living area that takes up more than half of the floor plan, with a huge double bedroom and bathroom occupying the remaining space. As indicated in figures 24 and 25, the project will construct five 3D-printed homes, each of which will get more sophisticated as different printing techniques and numerous storeys are used. It was built by printing layers of stacked concrete to make 24 distinct components and has curving, sloped outside walls. These parts were printed and carried to the plot, where they were assembled, secured to a foundation, and fitted with a roof, windows, and doors.

Fig.25: 3D printing process
Source:
https://www.designboom.com/architecture/project-milestone-first-3d-printed-concrete-house

"With the printing insulated and self-supporting wall elements curved in three planes, we've taken important steps in this project in the further development of 3D concrete printing in construction,"

Weber Benelux CEO Bas Huysmans

2.8 Suggesting Parameters of Analysis

Based on precedents, table 2 concludes the suggested parameters of analysis that are valid to be used in analysing the following case studies.

Table 2: Parameters of 3D printing technology applied to construction of sustainable houses.

Parameters of Analysis				
Technique used in 3D Printing	**The Structure (Stability)**	**Materials Used in Construction**	**Design Flexibility**	**Sustainable Features**

3. METHODOLOGY

This research will first follow a comparison between traditional techniques and 3D printing technology to study their impacts on sustainable houses, interpretation of the 3d printing works and analyze both its advantages and disadvantages. The research will follow a qualitative research method, where the information of theoretical study is presented through a literature review of previous readings, definitions of 3D printing, the advantages of disadvantages, and evolution throughout history. Then this study will follow a deductive and inductive method to analyze this data in a scientific framework through readings of references, scanning official websites, in addition to analyzing the parameters of 3D printing in case studies, and deducing the effective method and functions to achieve sustainable house. The case studies include international 3D printing projects chosen according to specific parameters such as:

- Parameter 1: Technique used in 3D Printing
- Parameter 2: Structure (Stability)
- Parameter 3: Materials used in construction
- Parameter 4: Design Flexibility
- Parameter 5: Sustainable Features

Therefore, the case studies will be as:

- Case study 1: TECLA 3D printed house, in Massa Lombarda, Ravenna, Italy 2021
- Case study 2: Dubai Municipality Building, UAE, 2019
- Case study 3: Beckum First 3D Printed house in Germany

The study will then compare the most significant cases between the three case studies. The case analysis demonstrates that it adheres to the three requirements of qualitative research methods: description, comprehension, and clarification as long as it fulfills the intended objective.

3.1 Analyzing Case Study I: TECLA 3D printed house, in Massa Lombarda, Ravenna, Italy

Architects: Mario Cucinella Architects

Area: 60 m²

Year: 2021

Lead Architect: Mario Cucinella

Location: Massa Lombarda, Ravenna, Italy

Building Type: Sustainable House

As shown in figure 26, the home, dubbed TECLA (a combination of the words technology and clay), was designed by Mario Cucinella Architects, and built and engineered by Wasp in just 200 hours. By blending the materials and spirit of timeless historic homes with the world of 21st-century modern manufacturing, the word TECLA conveys a strong link between past and future. It consists of a living zone with a kitchen and a night zone with amenities, with a total area of roughly 60 square meters and two modules reaching a height of 4.2 meters. It is the world's first 3D-printed home composed entirely of a mix of mostly local earth and water. The TECLA project is part of a wave of enterprises that are launching new projects because of additive manufacturing.

Fig.26: TECLA 3D printed house
Source:
https://www.archdaily.com/teclatechnology-and-clay-3d-printed-house- cucinella-architects.
Photograph: Iago Corazza

3.1.1 Analyzing Parameter 1: Technique Used in 3D Printing

Crane WASP, a WASP 3D printing technique, was employed to construct the structure. It's the world's first 3D printer that can print from the ground up and is modular and multilayer. It consists of software and, by 2021, a fixed fixture with two synchronized printer arms capable of printing a 50 m3 area each.

The dwelling prototype, according to the firm, blends traditional construction traditions with current technology to create recyclable, low-carbon, climate-adaptable housing. The earth mixture's composition adjusts to local climatic circumstances, and the envelope's infill is parametrically designed to balance thermal mass, insulation, and ventilation in accordance with climate requirements. Figures 27 and 28 show TECLA 3D printed houses and their 3D printing process.

Fig.27: Prototype of TECLA 3D printed houses.
Source: https://www.engineeringforchange.org/news/finally-credible-prototype-sustainable-3d-printed-housing.

Figs.28 & 29: 3D printing process of TECLA
Source: https://worldarchitecture.org/article-links/egmvf/mario-cucinella-architects

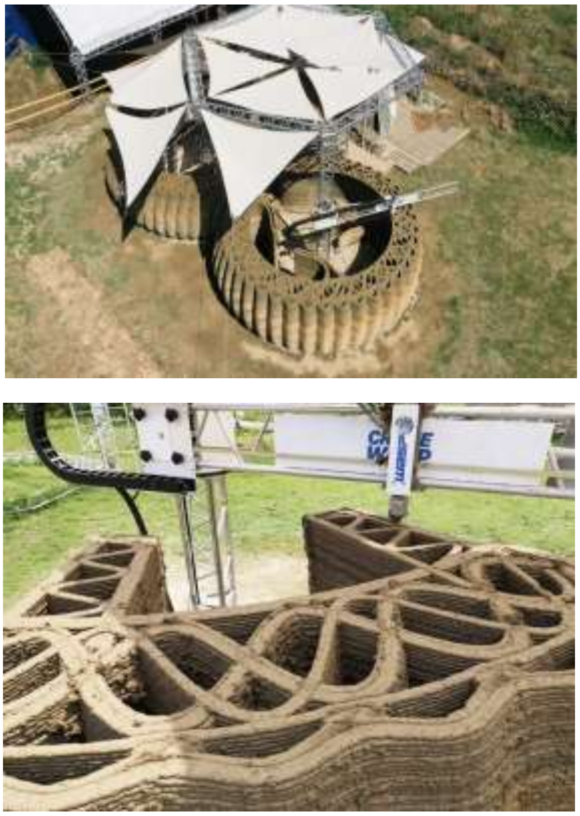
3.1.2 Analyzing Parameter 2: The Structure (Stability)

As shown in figures 30 and 31, the structures are dome-shaped and include a big glass entryway and ceiling windows. The single prototype has no windows and no paint on its walls as of 2021. 350 stacked layers of 3D-printed clay make up the ribbed outer wall. The clay is organized in undulating layers that serve as a thermal barrier as well as structural stability.

3.1.3 Analyzing Parameter 3: Materials Used

TECLA is a unique circular dwelling model that combines vernacular construction research, bioclimatic principles research, and the use of natural, recyclable, and locally sourced materials.

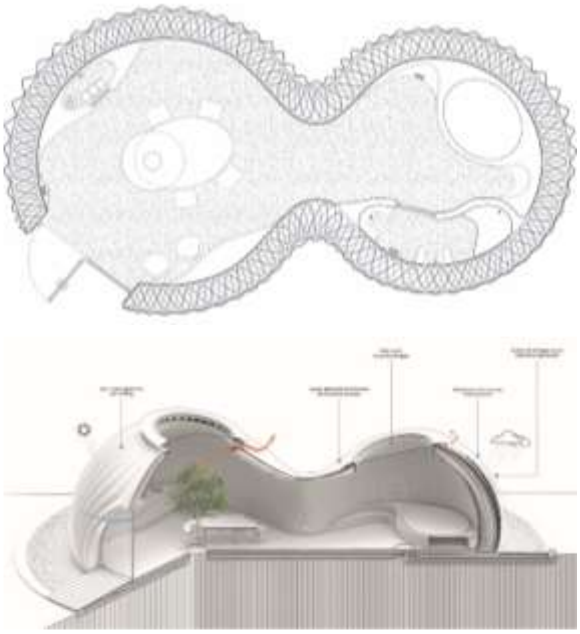
Local dirt mixed with water, rice husk fibers, and a binder make up the substance. Rice husk and rice straw from rice cultivation waste are used as infilling materials for thermal insulation. The 350 stacked layers of 3D-printed clay that make up the ribbed outer wall.



Figs.30 & 31: Undulating curved layers provide structural stability.
Source: https://www.archdaily.com/teclatechnology-and-clay-3d-printed-house-mario-cucinella-architects.

3.1.4 Analyzing Parameter 4: Design Flexibility

TECLA is made up of two continuous elements that end in two circular skylights that transmit the 'zenith light' through a sinuous and uninterrupted sine curve, while evaluating the building's design in connection to its climate and latitude. This can be noticed from figures 32 and 33. The envelope's distinctive structure, from the geometry to the external ridges, has allowed it to maintain structural balance both during the 3D printing phase and after the covering has been applied, resulting in an organic and visually harmony in appearance. This house's aesthetics are the result of much technical and material effort. It wasn't only a matter of aesthetics. It is a true and honest form (Cucinella, the architect of TECLA, 2021).



Figs.32 & 33: Plan and Section of the house
Source:
https://www.archdaily.com/teclatechnology-and-clay-3d-printed-house-mario-cucinella-architects.

3.1.5 Analyzing Parameter 5: Sustainable Features

The first eco-sustainable dwelling style made completely of natural, local raw earth and built using traditional methods. It's a near-zero-emission project, thanks to its casing and use of wholly local materials that reduce waste and leftovers. TECLA is a pioneering example of low-carbon housing because of this and the usage of raw soil. Buildings like the Tecla prototype might be very cheap, well-insulated, stable, and weatherproof, climate-adaptable, customisable, constructed quickly, require just a small amount of readily learned manual work, reduce homelessness, offset carbon emissions from concrete, and use less energy.

“TECLA responds to the increasingly serious climate emergency, to the need for sustainable homes and to the great global issue of the housing emergency that will have to be faced, particularly in the context of urgent crises generated, for example, by large migrations or natural disasters.”

Mario Cucinella Architects

3.2 Analyzing Case Study II: Dubai Municipality, UAE

Architect: Yves Behar
Area: 640 m2
Year: 2021
Location: Dubai, UAE
Building Type: Sustainable Building

According to the Guinness Book of World Records, the Dubai Municipality Building is the world's largest 3D printed construction, shown in figure 34. It stands 9.5 meters tall and covers an area of 640 square meters. Apis Cor, the first company to manufacture specialist equipment for 3D printing in the construction industry, completed the 3D printed wall constructions of a two-story administrative building for the Dubai Municipality. For constructing the World's Largest 3D Printed Building, Dubai Municipality won the UAE Ideas Award, held by the Dubai Quality Group under the slogan "Nothing is Impossible," in the category of "Innovation in the field of inventions."

Fig.34: Dubai municipality external view
Source:
https://www.archdaily.com/930857/dubai-municipality-to-become-the-worlds-largest-3d-printed-building

3.2.1 Analyzing Parameter 1: Technique Used in 3D Printing

The Apis Cor 3D printer is portable, and it was crane-moved throughout the construction site. Temperature and humidity were not controlled because the printing process took place in an open location. To 3D print the complete building's wall constructions, only three people and the machine were required. Without human interaction, the printing is done electronically according to engineering blueprints. It is carried out by using local components and 3D printing on-site under exterior working circumstances, as shown in figures 35 and 36.

Figs.35 & 36: Dubai municipality 3D Printing process
Source:
https://www.archdaily.com/930857/dubai-municipality-to-become-the-worlds-largest-3d-printed-building

3.2.2 Analyzing Parameter 2: The Structure (Stability)

The construction was built immediately in place (on site) using an innovative 3D printer. No additional assembly work was required. It's a two-part wall having an outside shell and a filler inside. The building's foundation is traditional, but the walls are 3D printed, and the reinforcing is "3D-printed formwork for columns manually filled with rebar and normal concrete." The 3D printing material used in this project is a gypsum-based mixture created by Apis Cor and manufactured locally.

Unlike the traditional technique of construction, which relies on the work of clamping wooden components with nuts and bolts, strengthening, concrete pouring, and brick forming, the walls are printed directly from the printer. Figures 37 and 38 show the 3D Printer used from Apis Core.


Figs.37 & 38: 3D Printer used from Apis Core
Source: https://www.archdaily.com/930857/dubai-municipality-to-become-the-worlds-largest-3d-printed-building

3.2.3 Analyzing Parameter 3: Materials Used

The municipality has made certain that the ingredients utilized in the blend are indigenous to the country. Apis Cor designed and produced the 3D-printed substance, which was a gypsum-based combination. As clarified in figures 39, 40, and 41. Walls are 3D printed, and columns are reinforced with 3D-printed formwork that is manually filled with rebar and normal concrete. This effort represents a significant advancement in the field of concrete 3D printing (Nikita Cheniuntai, CEO and founder of Apis Co, 2021).

3.2.4 Analyzing Parameter 4: Design Flexibility

The building was constructed using various curves and shapes to see if 3D printing could be used to construct a range of designs. The municipality had set up all the necessary infrastructure to deal with current building technology to achieve Dubai's 3D printing strategy, which aims to make Dubai a global hub for 3D printing technology.


Figs.39 & 40: Steel columns inside layering by human intervention
Source: https://www.archdaily.com/930857/dubai-municipality-to-become-the-worlds-largest-3d-printed-building

Fig.41: Material layering for walls
Source: https://www.archdaily.com/930857/dubai-municipality-to-become-the-worlds-largest-3d-printed-building

3.2.5 Analyzing Parameter 5: Sustainable Features

The program expands the role of 3D printing technology in construction cost reductions of 50-70 percent and labor cost reductions of 50-80 percent, as well as a 60 percent reduction in construction waste. It has a favorable impact on the sector's economic return and helps to achieve environmental and resource sustainability. In addition to employing locally sourced materials, the enhanced version will be more reliable and more efficient. The structure was constructed in accordance with sustainability and green building standards. It has efficient insulation systems thanks to revolutionary geometrical wall printing, and it expands the use of gaps inside the wall, which aids the building's thermal insulation and reduces energy consumption.

3.3 Analyzing Case Study III: Beckum First 3D Printed House in Germany

Architect: Mense-Korte architects
Area: 160 m² (80m2 each floor)
Year: 2021
Location: Beckum, North Rhine-Westphalia, Germany
Building Type: Sustainable house
Builder: PERI GmbH

As shown in figure 42, the two-story house, with around 80 sqm of living area per level, employs a method that was initially used in Germany.

Fig.42: The 3D Printed house external view.
Source: https://blog.allplan.com/en/first-3d-printed-house-in-germany

It is not simply a work of art, but it has already received the "German Innovation Award" for 2021.

North Rhine-project Westphalia's was financed with 200,000 euros from the state's 100-hour Innovative Construction Funding Program.

3.3.1 Analyzing Parameter 1: Technique used in 3D printing

The Beckum project uses Behrokh Khoshnevi's contour crafting method, where building materials are digitally built - layer by layer - without physical work, using BOD2 3D printers. It takes around 5 minutes to print 1m2 of a double-skin wall. As shown in figures 43 and 44, the house was built with a digitally controlled 3D printer that used a nozzle to apply a unique concrete. The printer can examine the pipes and connections for future utilities such as water, power, and other utilities. This gantry printer, which moves the print head along three axes on a metal frame that is permanently mounted. The BOD2 produces one meter of concrete per second, letting it the quickest 3D concrete printer available. Printing a double-skin wall, for example, takes 5 min / m2. (Peri, 2021).

Figs.43 & 44: The 3D Printing process
Source: https://blog.allplan.com/en/first-3d-printed-house-in-germany

3.3.2 Analyzing Parameter 2: The Structure (Stability)

The construction is made up of hollow walls with three layers of skin where between them there are insulating material. The printer must extrude two-centimeter-wide concrete sheets that are both strong enough to sustain each other and wet enough to chemically bond together. Figure 45 clarifies the 3D printing of the building's foundations.

Fig.45: The 3D printing of foundations
Source: https://www.archdaily.com/949531/3d-printing-for-residential-is-market-ready-germanys-first-building-is-under-construction

3.3.3 Analyzing Parameter 3: Materials Used

The material utilized was i.tech concrete 3D, which was created specifically for 3D printing by HeidelbergCement and is compatible with the BOD2. A nozzle that expelled special mortar and concrete was used to print the house. Gray concrete layers and circular shapes dominate the interior of the house. Concrete is also used to accentuate other features in the rooms, such as the fireplace and bathtub.

3.3.4 Analyzing Parameter 4: Design Flexibility

The shape is simple to include into the design. The additively made single-family house's exterior face stands out from the rest of the city: the concrete layers are plainly visible, and the home's shape is round rather than angular, as shown in the plan of figure 46. "3D printing allows a high degree of creative freedom that would be achievable in conventional building at tremendous financial expense," the architect says of the machine manufacturing approach (Mense-Korte architects, 2021).

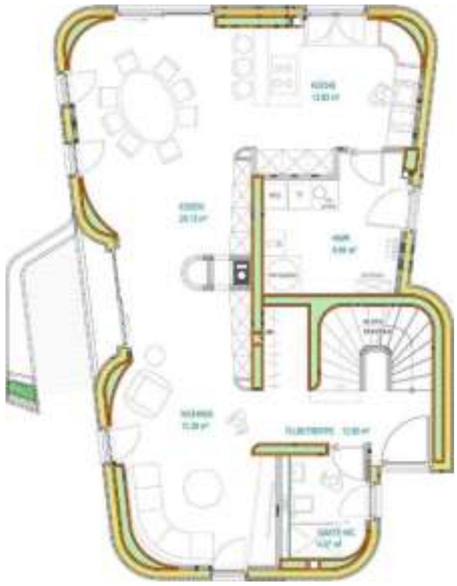


Fig.46: The plan of the house
Source:
https://blog.allplan.com/en/first-3d-printed-house-in-germany

3.3.5 Analyzing Parameter 5: Sustainable Features

The method of building reduces time and allows for the incorporation of more challenging structures and shapes into the design. It reduces the number of employees needed in the construction process, which is especially beneficial considering the industry's dearth of experienced personnel. On a sturdy metallic frame, a print head moves in three axes. This saves both time and money. When compared to other enormous forms of wall constructions, placing the printing mortar very precisely allows us to save up to 50% on material for the walls. Figure 47 shows the interior space that includes a chimney that was also 3D printed layer by layer.

We are printing at a slower rate than is technically conceivable because this is the first building of its sort. We aim to take advantage of this chance to get more knowledge in day-to-day operations so that we may better use our technology's cost-cutting potential in the future printing project. (Leonhard Braig, 2021).

Fig.47: The interior showing the chimney created also layer by layer.
Source:
https://www.archdaily.com/949531/3d-printing-for-residential-is-market-ready-germanys-first-building-is-under-construction

3.4. Comparison between the three case studies

The following table clarifies the comparison between the case studies as follows.

Table 3: Comparison table between the three case studies according to the five parameters

Project	Technique Used in 3D Printing	The Structure (Stability)	Materials Used	Design Flexibility	Sustainable Features
TECLA 3D printed house, in Massa Lombarda, Ravenna, Italy. Architects: Mario Cucinella Architects  	-A 3D printer that can print from raw earth -first 3D printer that can print from raw earth and is modular and multilevel stationary fixture with two synchronized printer arms that can simultaneously print an area of 50 m^3 each. -combines ancient building techniques with modern technology.	-The buildings are dome-shaped. -The only prototype has no windows and paint on its walls. -Ribbed outer wall that is made up of 350 stacked layers of 3D-printed clay -The clay is arranged in undulating layers that not only provide structural stability	-vernacular construction practices. -the use of natural, recyclable, and local materials. -The material consists of local soil mixed with water. - The infilling material for thermal insulation consi sts of rice husk and rice straw from rice cultivation waste.	-TECLA is a composition of two continuous elements -Organic and visually coherent design. - The building's shape in relation to its climate and latitude	-The first eco-sustainable housing model 3D printed entirely from natural, local raw earth, - very cheap, well-insulated, stable, and weatherproof, climate-adaptable, customizable, get produced rapidly -zero-emission project: its casing and the use of an entirely local material allows for the reduction of waste
Dubai Municipality, UAE. Architect: Yves Behar. - Area: 640 m2  	-3D printer is mobile and was moved around the construction site by crane undertaking 3D printing. -Only 3 workers and the machine were needed to 3D print wall structures of the entire building. -undertaking 3D printing onsite directly under external working conditions and using local components.	-The structure is built directly in place. -It is a wall with an outer shell and an inner filling. -3D-printed formwork for columns manually filled with rebar and regular concrete. - The foundation of the building is a conventional construction.	-The materials used in the mixture are local materials. - 3D-printed material was a gypsum-based mixture. - The walls are 3D printed and reinforcement put in place are 3D-printed formwork for columns.	- The building has been designed with different curves and shapes with modern technology in the construction field	- Saving construction costs and labor costs - Energy Efficient insulation systems through innovative geometrical wall printing. -reducing the percentage of waste -more reliable and time efficient, in addition to using locally materials.

Project	Technique Used in 3D Printing	The Structure (Stability)	Materials Used	Design Flexibility	Sustainable Features
Beckum First 3D Printed house in Germany. - Architect:Mense-Korte architects. - Area: 160 m² (80m2 each floor)  	-Contour crafting principle developed by Behrokh Khoshnevi, -Building components are digitally manufactured - layer by layer - without manual labor. - Using 3D printers of type BOD2 (fastest 3D concrete printer) for printing takes around 5 minutes to complete 1m² of a double-skin wall. -gantry printer that carries out a movement of the print head over 3 axes on a permanently installed metal frame	-The structure is made up of triple-skin hollow walls that are filled with an insulating material. - The two-centimeter-wide concrete sheets that the printer extrudes must be both strong enough to support	- The material used was "i.tech concrete 3D", which was specially developed by HeidelbergCement for 3D printing and is compatible with the BOD2. - Printed using a nozzle that ejected mortar and concrete. - in interior spaces also using of concrete layering	-The shape is easily implemented in the design. - The shape of the home round instead of angular. - 3D printing offers a high degree of design freedom.	- The method of construction saves time - Less number of people needed in the construction process. -The system has a print head that travels along three axes on a sturdy metallic frame, allowing the printer to move to any location within the structure and only needing to be calibrated once. This saves both time and money.

4. RESULTS

This research finds important features based on the table number 3 (the table of comparison between the three case studies). One of the most crucial elements influencing whether 3D printing will be used by the building sector is its ability to lower construction costs. As indicated in figure 48 of Venn Diagram, the factors that affecting and contributing to the overall cost of the sustainable house and its viability are:

a. Technique used in 3D Printing
b. Structure (Stability)
c. Materials used in construction
d. Design Flexibility
e. Sustainable Features

3D-printed homes are inherently durable, inexpensive, and built to last. They can help make homes more affordable and will be another tool for addressing the effects of the homeless and the climate crisis.

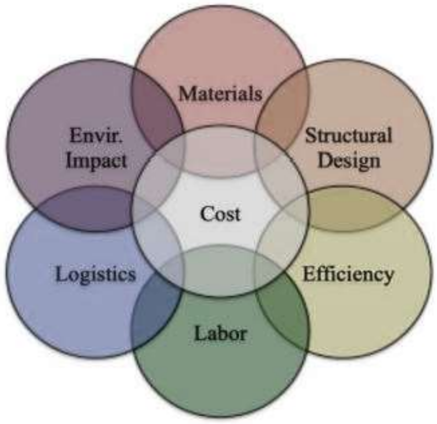


Fig.48: Venn Diagram Depicting the Relationship Between Cost and Viability
Source: https://www.maximizemarketresearch.com/market-report/global-3d-printing-material-market/9860

The resulting benefits of advancing 3D technology in sustainable houses are numerous, with the following being the most important:

a. Cost Savings
b. Use of low-embodied-energy raw materials
c. Decrease in on-site accidents
d. Time savings
e. Minimum waste
f. Enables the creation and fabrication of more complicated designs

For the five questions about 3D printing, it's easier, faster, better, and cheaper. Traditional homes, the question of whether respondents believe this Living safely in a 3D printed home had the highest positive response rate (89%). In summary, there is a consensus among respondents that it is a 3D printed home. It is superior to traditional homes in the following ways: Construction speed; cost; Environmental benefits; and security. Figure 49 indicates the 3D printing material market globally.

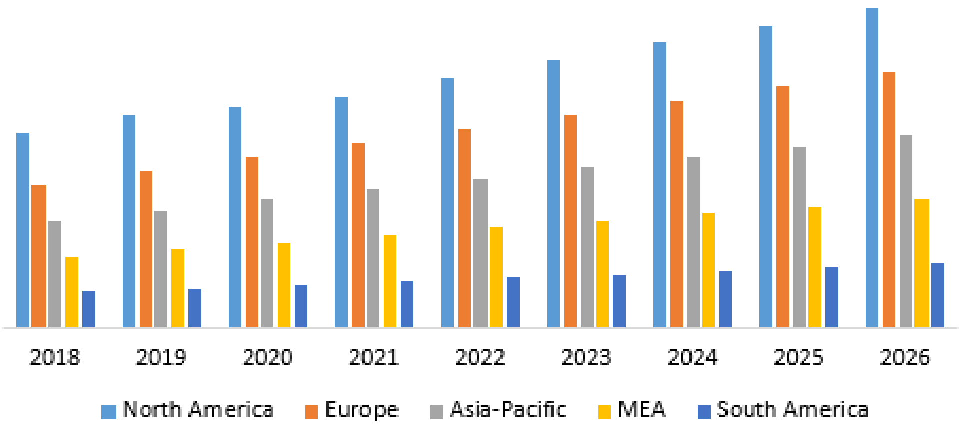


Fig49: Global 3D printing Material Market, by Region
Source: https://www.maximizemarketresearch.com/market-report/global-3d-printing-material-market/9860

5. DISCUSSION

With the aim of this paper to compare between traditional techniques and 3D printing technology to see their impacts on sustainable house, interpret of the 3D printing works and analyze both its advantages and disadvantages, the following points have been discussed:

a. There are some parameters affecting the application of the 3D printing technology on sustainable houses (such materials used, structure, design flexibility…), all well analysed in the three case studies and well compared.

b. 3D printing has the potential to alter today's architecture, it must be developed with sustainability in mind, both in terms of material selection and building approach.

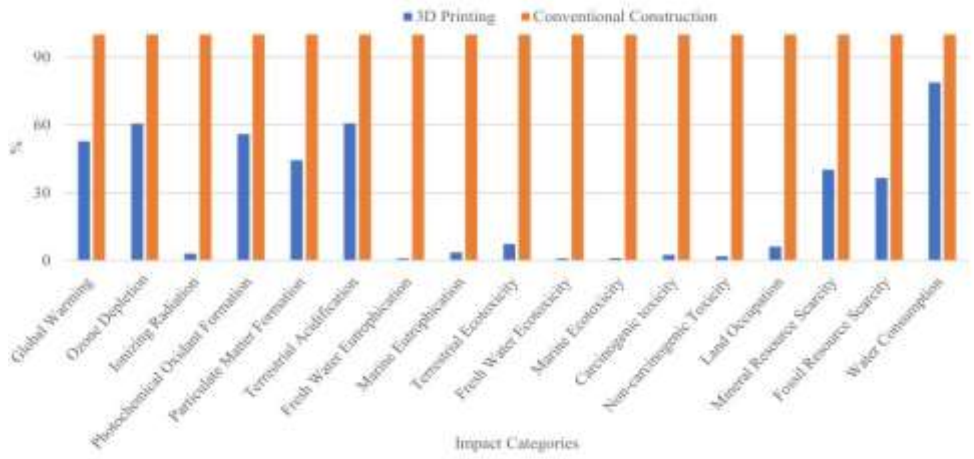


Fig.50: Relative environmental impacts of 3D printed and conventional constructed houses.
Source: Environmental Footprint and Economics of a full-Scale 3D-Printed House.pdf

c. There is big difference between the 3D printing technology of today and conventional constructing methods in terms of efficiency, environmental impacts, affordability, cost effective. Figure 50 shows a chart clarifying the relative environmental impacts of 3D printed and conventional constructed houses.
d. The concept of printing a full house used to seem like a much further invention. However, 3D printing is swiftly becoming the most promising construction solution.
e. Construction businesses have made significant progress in 3D printing homes in recent years. The ground breaking technology enables businesses to experiment with new structural shapes, cut waste and expenses, and increase construction site safety.
f. Despite its flaws, 3D printing technology is still evolving to become a viable, long-term housing solution. Firms are experimenting with novel processes and materials blends such as wine and bioplastics, as well as testing several printers on site to better accomplish projects.
g. 3D printed homes are getting more complex and accessible as building businesses continue to improve. With so many advantages and projects in the works, the debate is no longer whether 3D printing is a viable construction technique. Rather, it is about how we can best use technology to address the building industry's most pressing issues. Figure 51 highlights a statistical chart for the 3D printed houses (presented in orange) versus the conventionally produced houses (presented in blue). This chart proves by percentage that 3D printing houses are easier, faster, cheaper, and safer.

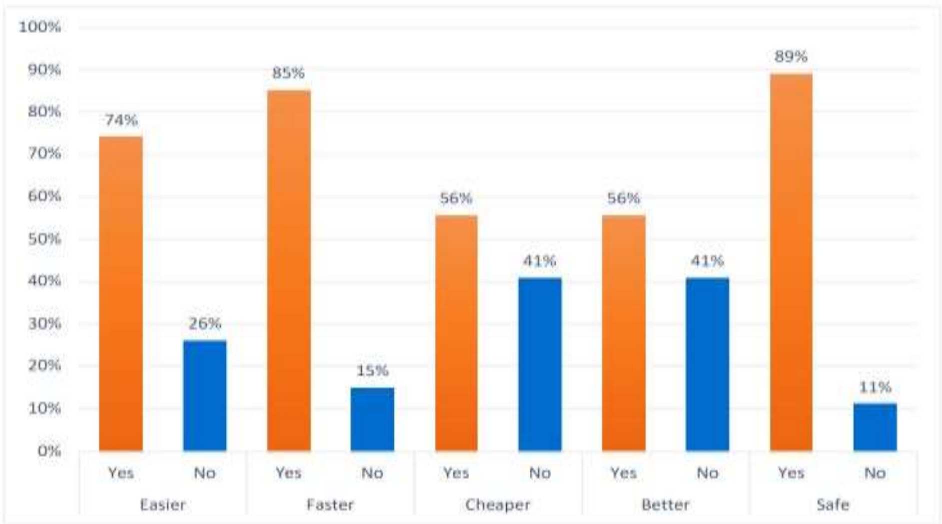


Fig.51: 3D-printed houses versus conventionally produced houses.
Source: https://www.uj.ac.za/wp-content/uploads/2021/11/social-technical-acceptability-report-16-may-2021.pdf

This research finds out how to apply 3d printing technology in the construction of sustainable houses. Difficulties in applying these technologies on a vast scale in the construction field are huge so there are several steps to be taken so these techniques can become viable. First, the 3d printing is yet considered as a new technology even the the idea was present long time ago, but the reliability on this technology is yet recent and it is limited to many important factors especially in the construction field when we are talking about big structures.

To solve the limitations regarding the scale we can decompose the building into chunks and print each floor by its own and if the floor is too big we can print each room by its own like capsules and assemble them on the site location, instead of building a huge 3d printing machine which will demands a lot of efforts and resources but also it wouldn't be logic to build a printer the height of the building.

Another point to limit the scale limitations is by reassembling the 3d printing machine on each floor during the construction phase, this will require a lot of efforts by the construction workers especially during the transportation of the parts from one floor to another using a construction crane.

6. CONCLUSION

3D printing, as an automatic layer-by-layer manufacturing process, is a promising era that may be utilized by the development enterprise to acquire economic, environmental, and different benefits. The use of 3D printing withinside the creation enterprise is exceedingly depending on the accuracy of the printing jobs, the provision of printing materials, the price of the printing process, and printing time, primarily based totally on which applicable 3D printing technologies. The use of 3D printing to major construction projects, the development of building information modeling, the levels of mass customization requirements, and the life cycle costs of 3D printed construction products / projects are all factors that influence its adoption. There are some qualifications as well.

In addition, the construction industry's degree of classification and individualization has been objectively evaluated. By addressing these obstacles, 3D printing in the construction industry is projected to attain its full potential. On the other hand, there may be some concerns that need to be addressed. An important unknown is whether the era of 3D printing will ultimately wipe out the work of hundreds of skilled workers. It is difficult to predict that 3D printing will replace traditional manufacturing in the coming years. With all technologies available in-house, 3D printing is likely to evolve with traditional technologies, especially to support them in more advanced and cutting-edge construction projects.

Acknowledgment

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