The Tectonic Use and Effect of 3D Printing in Construction Scale

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ABSTRACT

Nowadays, robotic technology and 3D (three dimensional) printing technology are contributing to several manufacturing industries. In the building construction, the 3D printing technique is an alternative construction method that getting attention from construction companies and developers. There is a great transformation in the way structural systems and materials are used due to the development of this century new design and production possibilities; specifically, in the production process in which robots are used. As a matter of fact, 3D printing technology has numerous advantages to people, architects, engineers, and governments trying to develop their countries. Due to its promising results, the National Aeronautics and Space Administration (NASA) has considered the 3D printing technology to be used on Mars. This thesis deals with the tectonics use and effect of 3D printing technology in the architecture and construction sector.

The aim of this study is to develop the relationship between robotic productions and architecture, which became noticed recently and more obvious with the emerging of 3D printer technologies. In this context, one of the objectives of this thesis is reconsidering the architecture vision and investigates the way tectonic formation of the buildings built with a 3D printer.

To answer the question of where architectural tectonics developed along with design and production examples, it is gained importance to investigate the conceptual meaning of 3D production and tectonics through examples representing the 21st century architectural language.

In this context, three 3D concrete printed building selected. Both they are located in the “Gulf Region” of Middle East. The selected examples are analyzed from tectonic point of view considering different theorist’s theories (like artistic value of structure, montage, art of joints, and stereotomics). In addition, the effects of 3DCP technology, which seems to increase the time, cost and sustainability of building construction, have been evaluated in this context. This way of construction gives flexibility and freedom to the architectural design and engineers to build our future environment.

Keywords: additive manufacturing, 3D printing, tectonics, 3D concrete printing.

ÖZ

Günümüzde robot teknolojisi ve 3D (üç boyutlu) yazıcı teknolojisi birçok imalat endüstrisine katkıda bulunmaktadır. Bina yapımında, 3D baskı tekniği, inşaat şirketlerinden ve geliştiricilerden dikkat çeken alternatif bir inşaat yöntemidir. Bu yüzyılın yeni tasarım ve üretim olanaklarının gelişmesi nedeniyle; özellikle, robotların kullanıldığı üretim sürecinde, yapısal sistemlerin ve malzemelerin kullanım biçiminde büyük bir dönüşüm var. Nitekim, 3D baskı teknolojisinin ülkelerini geliştirmeye çalışan insanlar, mimarlar, mühendisler ve hükümetler için sayısız avantajları vardır. Bu gelecek vaat eden sonuçları nedeniyle, Ulusal Havacılık ve Uzay Dairesi (NASA) 3D baskı teknolojisinin Mars'ta kullanılmasını düşünmüştür. Bu tez, mimarlık ve inşaat sektöründe 3D baskı teknolojisinin tektonik kullanımı ve mimari etkisi ile ilgilidir.

Bu çalışmanın amacı, 3D yazıcı teknolojilerinin son zamanlarda daha açık bir şekilde ortaya çıkmasıyla, robotik üretimler ve mimarlık arasındaki ilişkiyi geliştirmektir. Bu bağlamda, mimari görüşün yeniden gözden geçirilmesi ve 3 boyutlu yazıcı ile inşaa edilen binaların tektonik oluşumunun araştırılması bu tezin amaçlarından biridir.

Tasarım ve üretim örnekleri ile birlikte mimari tektoniğin nerede geliştiği sorusunu cevaplamak için , 21. yüzyıl mimari dilini temsil eden örnekler üzerinden, 3 boyutlu üretim ve tektoniğin kavramsal anlamını araştırmak önem kazanmıştur.

Bu kapsamda, üç adet 3D yazıcı ile inşaa edilmiş beton yapı seçildi. Hepside Orta Doğu'nun “Körfez Bölgesi” nde bulunmaktadır. Seçilen örnekler, farklı teoristlerin teorileri (sanatsal değer, montaj, birleşim sanatı ve streotomik gibi) dikkate alınarak tektonik bakış açısından analiz edilir. Ek olarak, bina inşaatının zamanını, maliyetini ve sürdürülebilirliğini artırdığı görülen 3DCP teknolojisinin etkileride bu bağlamda değerlendirilmiştir. Bu inşaat şekli, mimari tasarım ve mühendislere gelecekteki çevremizi inşa etmeleri için esneklik ve özgürlük sağlar.

Anahtar Kelimeler: katkı üretimi, 3D baskılı yapı, tektonik, 3D beton baskı.

DEDICATION

I dedicate this thesis to God “Allah”, who is always beside me, who gave me and my beloved once a healthy life, strength, and kept me motivated.

This thesis is dedicated to my beloved parents, who gave me strength and motivation when I thought of giving up and have been my source of inspiration, who provided me with emotional, spiritual, and financial support. My dear father who worked hard to provide my family and me with everything we need, who always encouraged me to be the best that I can be. My dear mother who gave me endless love. My sisters who are always there when I needed them.

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Chapter 1

INTRODUCTION

1.1 General Overview on Additive Manufacturing

In 1981, the study of the manufacturing of printed solid model, which was the starting point of the “additive manufacturing”, “rapid prototyping” or “3D printing technology (Hideo Kodama, 1998), was both studied and published by Hideo Kodama of Nagoya Municipal Research Institute (Nagoya Japan). Throughout history, the selection of materials, their use, and the ways of the building have been discussed in architecture. Especially with the Industrial Revolution that started in the 18th century, the developments in the field of industry and technology have enabled new concepts, new materials, and new forms of production in the discipline of architecture. Today, recent technologies and innovative materials enable architects to follow a new process that designs the design process to optimize traditional “design and manufacturing” forms, while computational design and manufacturing technologies have encouraged architects to use new construction methods. The results of making homogenous structures, that are built using materials sourced from centralized factories, are derived from contemporary construction techniques that are often slow, labor-intensive, dangerous, expensive and constrained to primarily rectilinear forms.

Nowadays, technology has reached far enough in construction and architecture to utilize our experiences in a vast way, to express our designs in a different and better way. 3D printing is an advanced manufacturing process that can produce shape geometrics automatically from a 3D computer-aided process. In particular, the integration of three-dimensional printer technologies and robotics into the production process challenges designers to rethink the material's usage patterns, assembly, and related connection details. In this context, digital design and production methods and automated construction techniques have to change the effects of tectonics by utilizing traditional materials scilicet adobe, concrete, steel, and timber with digital tools; they also started to be interpreted in design and construction tectonically.

3D printing technology, also known as additive manufacturing (AM), was introduced to reduce the time required to produce prototypes with complex geometries in rapid prototyping manufacturing. With a growing interest is shown by architects' projects, it is usually showing the possibilities of these processes. The technology is known to produce single objects, small series, and prototypes, mostly in plastics or metals. Nowadays, 3D printing technology is utilized in several manufacturing processes such as aerospace, automotive, food, health, fabric, electronics, building construction sector, etc. For that reason, developers have developed different types of 3D printing techniques and machinery.

As sustainability is an important factor in any new technology. The 3D printing technology appears to be more sustainable than in some cases. It depends on the design of the form and material used to determine whether it is more sustainable than conventional building methods or not. Economy is one of the values that specify structural guidelines related to form. Searching for and finding the best form in terms of economic is attainable (Hurol, 2016).

1.2 Aim and Objectives of Study

This thesis aims to integrate robotic productions with architecture, which we have begun to see in recent years, especially after 3D printer technologies, and to requestion the object of architecture and to investigate how the tectonics that formed and developed. Various concepts concerned with the subject of 3D printing in the construction scale have been researched in previous literature. For instance, many researchers also gave the valuable contribution to this subject with their master or PhD thesis.

Beim (2004) in her thesis “Tectonic Visions in architecture– Investigations into practices and theories of building construction. Six case studies from the 20th century” from 1999 and in the publication “Tectonic Visions in Architecture” from 2004 that developed and elaborated the thesis. Beim argued that architects had a continuing ability to create tectonics in the new context and demonstrated this through the works of six architects that were inspired by the industrial materials, technology and principles.

Hurol (2016) in her book “The Tectonics of Structural Systems” about the ontological values of production processes. In this book, Delanda and Frampton approaches are combined, taking into consideration all values of architecture at the same time. The idea of inability to separate the tectonics of any building from its building technique and structure is supported in this book. In case if they are separated, architects would not be able to play with the structure or to follow structural engineers' recommendations.

Sabur (2019) in her thesis ‘Robotics in Architecture and Hybrids Tectonics of 21st Century’ argued that computational design techniques with digital design and production methods revealed hybrid tectonics. By considering possibilities of digital programmes the tectonics with the use of traditional materials such as concrete, steel, wood and brick have been hybridized with digital tools and new materials like granular materials and FBR have also begun to be interpreted in design and construction.

It is obvious that architectural tectonic has important place in architectural theory. Moreover, these researches show how tectonic theories studied and how different approaches are made in the field of architecture. However, these studies also show that there is no contribution about 3D printed buildings in the views of architectural tectonics. As a result, the gap in literature was defined.

The new design and production possibilities of the new century greatly transform the use of structural systems and materials - especially when robots are involved in the production process. Investigating the concepts of precise production and tectonics that the architectural production has just met, examining the examples that form the new language of the 21st-century architecture is important in terms of questioning where the architectural tectonics has evolved along with the design and production examples.

This thesis focusses on the use of 3D concrete printing (3DCP). As the 3D concrete printing technology is able to 3D print building elements and full buildings. This thesis is limited to fully functional structures “livable space” as architectural designed. In addition, it addresses the uses of 3D concrete printing in the Gulf Region as the three selected cases have played an important role in developing and improving the technology. To achieve a clear understanding of the technology and its benefits, three existed 3D concrete printed buildings from the Gulf Region are selected to be analyzed and evaluated according to the preset parameters.

1.3 Research Methodology

This thesis is based on a qualitative "analytics" methodology in order to accomplish the research objectives. Therefore, this thesis is divided into four main parts:
The first part is a description of the intentions, and questions about research orientations of this study by providing a methodological and theoretical framework. The data collection method is allocated to a literature review through articles and books in order to collect theoretical data. The information collected from previous studies and literature will create a general perspective of the tectonics theory.

The second part is to collect information regarding the history of 3D printing technology, the uses of the technology in manufacturing, and the introduction of the technology to architecture and the building construction industry. This part will also provide information about the 3D printer and material that can be used in the architecture and building construction sector. Consequently, the focus moves toward the use of 3D concrete printing (3DCP). Therefore, the rest of the study will be limited to 3D concrete printed buildings.

Third part is divided into two sections which are:

- First section, the chapter introduces three cases which are located in the "Gulf Region" of Middle East. The general information of the cases is provided in this part of the study.
- The second section will study and analyzes the cases according to their structures and building methods, design tectonic characteristics, and sustainability. The cases

are analyzed by observing the exterior and interior of each case through images and relying on some sources from literature.

The fourth and final part of the study is the evaluation of the technology. The 3D concrete printing technology is evaluated according to the specified parameters which are cost efficiency, time reduction, and ability to create curved forms from tectonic point of views.

1.4 Thesis Outline

The reader can achieve an outstanding knowledge of the tectonics use and effect of 3D printing (Additive Manufacturing) in construction scale by reading this thesis. Five chapters create the main outline of this thesis. The following descriptions are a short summary of the thesis structure.

Chapter 2 is introducing the concept of tectonics “architectonics” and the concept of techne in tectonics to achieve a clear understanding of the subjects. The information is allocated to a literature review through books and previous studies.

Chapter 3 introduces the history of 3D printing technology and the uses of the technology in manufacturing. Information regarding the general types of 3D printers are listed. The information will gradually concentrate on the uses of the technology in architecture and the building construction industry. The types of large-scale 3D printers and materials used parallel with the 3D printing technology in construction are provided in this chapter.

Chapter 4 consists of case studies and evaluation. This chapter is equivalent to the analysis that been done in previous chapters. The chapter is divided into three sections.

Firstly, the chapter will introduce the three selected cases. The cases design tectonics, construction process and structure, and the sustainability are analyzed. The design tectonics criteria of the cases, which are structure representation of art, joint, montage and stereotomic by the tectonic theoretician Botticher, Semper, Hartoonian, and Frampton, are summarized and listed. After that the advantages of the technology are listed and 3D printing technology in construction scale is evaluated according to their cost, construction time, form curvature. All the cases which are Dubai Municipality, Office of the Future, and 3D Studio 2030 are located in the Middle East.

Lastly, Chapter 5 is a brief conclusion which is summarizing the outcomes of this thesis and define the results and findings of the study with final thoughts.

Chapter 2

TECTONICS IN ARCHITECTURE

This chapter is divided into two sections to explain tectonics theory. The first part of the chapter will elaborate the concept of tectonics theory in architecture. The second part will acquaint the concept of techne in tectonics.

2.1 The Concept of Tectonics Theory "Architectonics"

From the Greek word 'Tekton', the word 'tectonic' has emerged. It was used to refer back to the builder, 'the carpenter' or maker in general. Then it started slowly to be used to point to the constructive arts more commonly. A multi-disciplinary approach that combines all the knowledge of each professional practice and application engaged with built environment shaping has to be taken into consideration when pointing to architecture in a contemporary context. The concept of architectonics is considered a newer term for tectonic (Frampton, 1995).

Tectonics in architecture is defined as the science and art of construction, both are in relation to create an artistic design. This doesn't only refer to the activity of making certain needs like materially requisite construction, but also to the activity that helps make this construction to an art form. Tectonics is a simple way of relating materialization and making of buildings whereby structure, experience, and use (Hartoonian, 1994:3). Tectonics is concerned with how the form elements are designed and joined to create an architectural synthesis. Therefore, what is meant by tectonics in this sense is the correlation between the form principals, basic idea, the method of building, and the present construction within a specific building (Beim, 2018). It can also understand tectonics as intelligence embodied in the mutual relationship between the parts that create an architectural piece (Hartoonian, 1994:10). Constituting a dimension of aesthetic, this could be argued as recognition of intelligence (Hartoonian, 1994:8). Tectonics can be seen at various levels in architecture. These architecture levels range from the conventional Japanese wood joint to spatial organizational tectonics to formal (Şahali, 2009). Critics and practitioners from all over the world agreed on not considering architecture as the art of representation nor scenography. As the rate of using technology for imagery production is at an alert condition, this view became more recognized. However, by using the technology itself more meaningful and creative characteristics of creating architecture can be achieved. The advantages of these characteristics cannot be taken without experiencing real aspects of tectonics in architecture.

Tectonic expression can be taken and discussed in a wide range of terms. It can be thought of in terms of the way in which structure and enclosure affect each other. The structure's presence representation is depending on the modulation of the enclosure, yet the structure that has been modeled remains obvious and apparent. The following discussion will also be concerned with this range. The connection between the construction idea and the construction itself is what concerns the representation in tectonics. It is all about the relation of representation of signification. As Panofsky states (Billington, 1979):

> " ...to perceive the relation of signification is to separate the idea of the concept to be expressed from the means of expression. And to perceive the relation of construction is to separate the idea of the function to be fulfilled from the means of fulfilling it."

The main focus of tectonic is on how the building is made and how the building method and the process itself can be seen in the construction. The building's all aspects of design and the program of requirements development are from the tectonics demands. Moreover, the building 's appearance on the city and detail scale must be taken into consideration in addition to connecting these aspects to technologies, structures, and materials options.

In fact, there is a correlation between tectonics in architecture and expressions of details. Moreover, the concept of tectonics in architecture has also been associate with materials' structural systems and technologies of production. This means those tectonics spot the light on how the details, structures, materials are important parts of designing. Acknowledging and celebrating the construction of buildings having multidisciplinary and international character is the goal of tectonics. Therefore, the role of tectonics is obviously important in the world of building. The concept is covering the shared development of constructing buildings and their design. It also refers to and covers the purpose of making the building and the used technology.

For example: Bötticher suggested two main elements of tectonics as kern form=basic/core form (the structural core of the building) and kunst form=symbolic/art form (the explanation of the structural form through ornaments). In other words, structural form indicates that each part of structure should be necessary for mechanical purposes and statical functionality. On the other hand, the art form indicates meaningful representation; a kind of characteristic in which the way the structure becomes visible. According to him, both of them are essential parts of tectonics. Unlike Semper, Bötticher’s division on core form and art form is more related to the form of the building rather than material, detail or construction. (Hartoonian, 1994: Frampton, 1995 : Şahali, 2015).

According to Francesco Cacciatore, “ the term stereotomic, from the Greek stereos (solid) and tomia (cut), introduces an idea of building, which is not conceived as the assemblage and juxtaposition of elements typical of the tectonic approach, but rather as the gradual removal of matter from an initial shape.” (Castellón & D’Acunto, 2016). According to this perspective, stereotomic approach implementation to architecture lead to monolithic and compact forms creation. Individual parts in this case can't be distinguished from the whole, and the planned spaces of architecture is produced by the removal of matter (Cacciatore, 2016). The constructive and technical features of a building is the main emphasis of the tectonic approach. Even though details were given great attention by Semper in his theory of tectonics, details importance was less than tradition, both in tectonics and stereotomy details are important. However, tectonic approach lays emphasis on expressing details. Stereotomic approach is based on creating voids and defining the building boundaries. Thus, space and structure are produced at one time through accumulating and distributing the matter.

Additionally, Frampton (1995) also explained it as ‘the art or technique of cutting solids’. Despite, its dictionary definition and word meaning of stereotomy which emphasize the significance of the cutting technique of solids, in Semper’s definition, the concept of stereotomy is considered as massive solid, heavy materiality on structures.

Frampton has a different frame by the three different values of the ‘tactile’. The telluric and tectonic which the idea of space is framed in such a way that slowly transforms the concept of space again. This alternative now tends to shift those parts that are visible from the building, and therefore can be attached to categories of visual arts for the benefit of the detailed privilege of the joint as the essential tectonic element: category classified as non-visual and non-representational that Frampton has attributed to Gottfried Semper, from which the fundamental connection of a building is formed in his point of view, in other words, it has come to be expressed as a presence in itself (Ballantyne, 2013). The joint category as the primary expression of a point where two forces meet, and the correlativity of the dis-joint in which elements can be separated. It is the important fulcrum in which a material, system, or surface connect. The material joint particularly has been regarded of the most significant aspect of architecture for many. According to Semper joint is the ultimate architectural (Maulden, 1986).

On the other hand, Hartoonian‟s book 'Ontology of Construction: On Nihilizm of Technology in Theories of Modern Architecture' (1994) notes an important change in the relationship between design and construction. This chance is occurred when techne shift with technology. Additionally, the theme 'Montage' is very important for him and he stated that this is the way of creating 'art of construction'. It can be said that his notion of montage emphasizes fragmentation like parts and whole.

Montage in the tectonic theory is about pre-manufacturing, the assembly, and the operation of material construction. In the other hand, it is an aesthetic tactic formed on 'heterogeneity' and 'juxtaposition' (Bundgaard, 2013). According to Bundgaard, montage is strategy to symbolize architecturally the way the tectonic theory is susceptible perceiving the potential of heterogeneous and perceived quality in developing new digital technologies (Hvejsel, Beim, & Bundgaard, 2015). The concept of assemblage indicates an understanding of architecture from bottom to top as it tends to be a dynamic which is appeared in complex systems where digital technologies emergence is characterized. A mere top-down understanding of architecture, as referred by the montage, deliberately orchestrated by the architect. Which was also envisioned in the classical master builder.

2.2 Concept of Techne in Tectonics

Tectonics can be explained as well through the study of the origin of words. It can be compared with terms such as technique, techne, and technology. As mentioned by Porphyrios, the Greeks had one phrase for art and craft to be mentioned at the same time which is techne (Şahali, 2009). This is because to them, artists and craftsmen are the same they called both technites, they did not differentiate between them (Porphyrios & Papadakes, 1982:59). The word “Techne” means a kind of knowledge that indicates the person’s intelligence by the Greek. This intelligence can be seen and noticed in constructing products in medicine, music, sculpture, poetry, agriculture, carpentry, and architecture. According to Porphyrios, the word “techne” is often applied to an opposed idea to nature. For example, production orderly knowledge is taken to convert raw materials into useful tools and this contradicts natural things as it shows the process of making. (Porphyrios & Papadakes, 1982:64).

In addition, it was stated by paragraph Hartoonian that technology is what is meant by the Greek word 'Techne'. The philosopher Heidegger who is considered one of the most responded philosophers to the cultural impact of technology identifies techne as being revealing and poetic. He viewed it further more than being a craftsman's skills and actions. To him, techne has also the meaning of fine arts and the art of thinking. It is the ability to do something well and perfectly. In this regard, "techne belongs to bringing-forth, to poiesis; -a Greek word, which means it is something poetic" (Heidegger, 1992:318). Techne is not concerned about showing how things are made or manufactured but concerned about exposing the intrinsic nature of things. At the same time technology shows as "a mode of revealing" (Heidegger, 1992:319). The ending, methods, and instrumentality have great significance in a world where the essence of materials is brought to light. Here "instrumentality is the fundamental characteristic of the contemporary technology" (Heidegger, 1992:318). However, contemporary technology has been also criticized by him too.

An understanding of technology in architectural classical agreements does not exist. Thus, today it is obvious that "The absence of structural utility as a theme in the architectural discourse of classicism was caused by an ontological relationship between meaning and work" (Hartoonian, 1994:2). To put it in another way, according to the legacy of Cartesian and Galileo's acquired cognitive inspiration with classical thoughts. The process in which building becomes a factor that determines the cultural characteristics and values of the finishing product, three fundamental changes appear, which relates to the 'concept of fabrication', 'new understanding of classical order', and 'concept of beauty' (Hartoonian, 1994:5). This has helped to dismantle the classic full understanding of the relationship between the "method of construction" or "art and science" in general, which was the old meaning of Techne. Techne signifies the logos of making: a concept of fabrication in which technique is congenial with the image of the final object. Though, with the discussion of Vitruvian and Palladian discourse on architecture (Hartoonian, 1994:29). As a result, towards the end of the 17th century, separation of engineering and architecture took place (Hartoonian, 1994:29).

The word “techne” has been replaced with “technique” in the 17th century (Şahali, 2009). The technique is the method by which technical elements of art or craft are used. Form problems can't be overcome by using building techniques as it is not a tool for that but rather considered as a reference one can go back to it when taking into consideration architectural spatial form (Giedion, 1967). The help of techniques is a must in order to improve technology and thus technique and technology are closer to each other.

In the 18th-century, the technology term became known on the basis of technique and the ontological relation between art and technique vanished (Hartoonian, 1994:36).

Technology is defined in the dictionary as “ An application of knowledge to the practical aims of human life or to change and manipulate the human environment.” Technology made our lives easier, as it incorporates the way tools, power source, materials, and techniques are used” in the 17th-century. Making things happen is what technology focuses on, unlike science which is mainly focusing on the way things happen and the reasons behind. Technology has strongly and positively affected human efforts and goals, especially when they started to use tools and equipment. Accelerating developing technology coincided with the Industrial Revolution but this had a cost as it caused environmental unwanted effects such as air and water pollution.

In Giedion's point of view, using modern technology in the tectonics field indicates how new techniques, building methods, and materials should be used to achieve creating a harmonic structure. This enabled producing new spatial forms in which architecture and site context cannot be separated. Eventually, architecture has a great role in civilization and it can be considered as the carrier of culture (Giedion, 1967; Frampton, 1992).

Architecture is not just about creating buildings and spaces. It is also the way new techniques and knowledge are applied. In fact, technology in architecture and society is important because it sets the boundaries of possibility. It serves as a mechanism for structuring the culture of our buildings. The available technology impacts the architecture language. Likewise, technology should be affected by the changes in the architectural language. It is important to understand the concept of tectonics to understand the idea of technology and approach to it.

Throughout history, technology played a significant role in architecture. That can be seen on the built environment these days. Technology has helped architects and engineers to achieve what was impossible before. Technology, in general, keeps improving our life quality in a fascinating way. One of those technologies is 3D printing which also called additive manufacturing (AM). In the last few years, new effective technologies have been used in the advance manufacturing industry which is 3D printing technologies. The technologies are receiving tremendous attention in architecture, due to potential use for direct building construction and the possibility to print complex structures, also of considerable dimensions (Cesaretti, Dini, De Kestelier, Colla, & Pambaguian, 2014). Architecture gained a new dimension and meaning by the invention of 3D printing technology. That enables architects and designers to express their ideas and make it possible.

As a result of chapter 2 it can be said that the most influential figures among theorists are Botticher, Semper, Hartoonian, and Frampton. In the rest of the study, the highlighted theorician’s concepts will play a big role as creating evaluation criteria. Accordingly, it might be meaningful to create an evaluation criterion for the 3D printed buildings from tectonic point of views. Table 1 shown how the theories take in consideration.

Table 1: Design Tectonic Criteria

Botticher	Semper	Hartoonian	Frampton
Artistic Value of Structure	Art of Joint	Montage	Stereotomic

Chapter 3

3D PRINTING IN CONSTRUCTION

The main aim of this chapter is to provide information regarding 3D printing technology (Additive Manufacturing) from the literature. The literature review includes publications such as review articles or research previously done by others. The chapter will discuss the types of additive manufacturing technology, and the uses of technology in manufacturing. Henceforth the chapter will provide information regarding the technology in the architecture and construction sector.

3.1 An Overview of 3D Printing (Additive Manufacturing)

3D printing is considered a robotic technology that uses successive addition of materials to form physical objects. It is an operation that is used to generate a three-dimensional solid object of almost any shape starting from a digital model. It is one of the techniques that are presently adopted by the industry in addition to other manufacturing processes. Since, the first commercialized 3D printing processes started, in 1980 by Charles Hull (Holzmann, Breitenecker, Soomro, & Schwarz, 2017), technology has developed and the usefulness of these machines has increased adding to that, they became low-priced.

For the last decay, 3D printing technology primary implementation focused mostly on reducing the time required for rapid prototyping which are complex in geometries (ISO / ASTM52900-15, 2015). 3D printing can be useful in lowering the construction cost and reducing carbon footprint. Moreover, it could make the labor safer, more effective, and reduce the building time significantly. This technology has started since the 80's but has not been dived into architecture till recent.

It has been growing and utilized since then in many fields. In fact, 3D technologies are utilized by aerospace, automotive, food, health and medical, fabric and fashion, electric and electronic, and lately in architecture and building construction industry. When a technology is an effective and good to the extent that it can be used in human body which is one of most difficult and sophisticated fields, then it is worthy to be used in any other area. The National Aeronautics and Space Administration (NASA) is one of the supporter and adapter of this technology (Litaker et al., 2013).

3D printing, in the context of Architecture, is still in its prime but show a lot of promise. Right now, 3D printing is slowly showing progress in becoming an important tool in the process of construction and whole design. The use of this technology has made a huge impact on cost, economic market, safety and time as well.

3.2 General Types of 3D Printing

3D printing technology has been improved with various functions. The additive manufacturing processes standards have been set by The American Society for Testing and Materials (ASTM group) (Fotheringham, 2016). Based on ASTM Standard, the 3D printing technologies are classified to seven types, " including the material extrusion, directed energy deposition, binding jetting, material jetting, sheet lamination, powder bed fusion, and vat photopolymerization" (Shahrubudin, Lee, & Ramlan, 2019). It has not been determined which technology function better than other as each of them aims at its own applications. Previously, 3D printing technologies were used to make a prototype only but nowadays, they are increasingly being used to make different kinds of products (Wang, Blache, & Xu, 2017).

A new 3D printer (Figure 1) which assumed to be able of printing around half a yard (46 cm) per hour at record time has been developed by Northwestern University researchers in Illinois (Carlota, 2019). This system is called High-Area Rapid Printing (HARP). It is on patent-pending from SLA technology. Most of the time, pursuing larger parts negatively affect speed, throughput or resolution. Thus it a challenge and most researchers are working on to avoid affecting these aspects. (Shahrubudin et al., 2019).

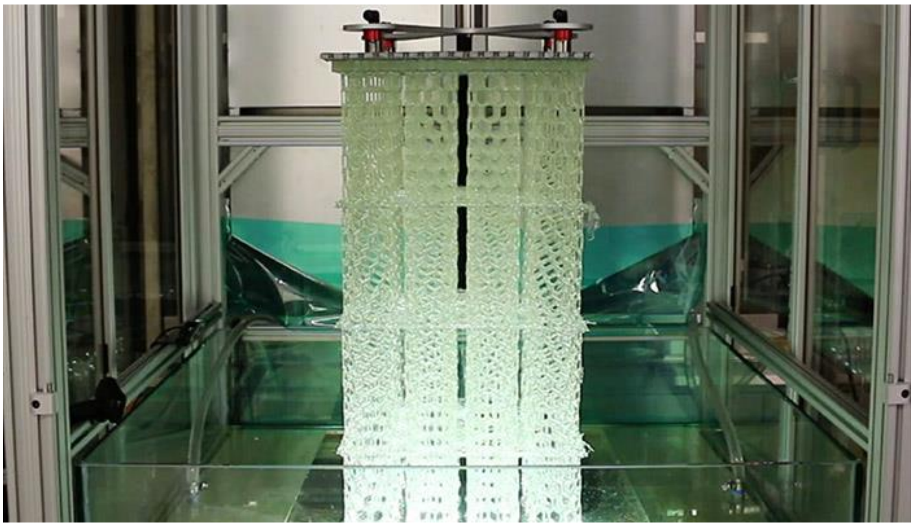

Figure 1: HARP (High-Area Rapid Printing) (URL 1)

3.2.1 Binder jetting

Binder jetting is a three-dimensional printing process, and rapid prototyping (Figure 2). To join powder particles liquid binding material is deposited. The binder jetting technology form the layer by using jet chemical binder onto the spread powder (L. Ze-Xian, T.C. Yen, M. R. Ray, D. Mattia, I.S. Metcalfe, & D. A. Patterson). This technique enables the production of metallic and ceramic parts as well as samples for casting patterns, also it enables printing different materials including sands, polymers, hybrid. It is worth mentioning that some of these materials like sand does not require additional processing. Moreover, binder jetting can also print very large products. The process of binder jetting is characterized by being simple, speedy and affordable as powder particles are glued together.

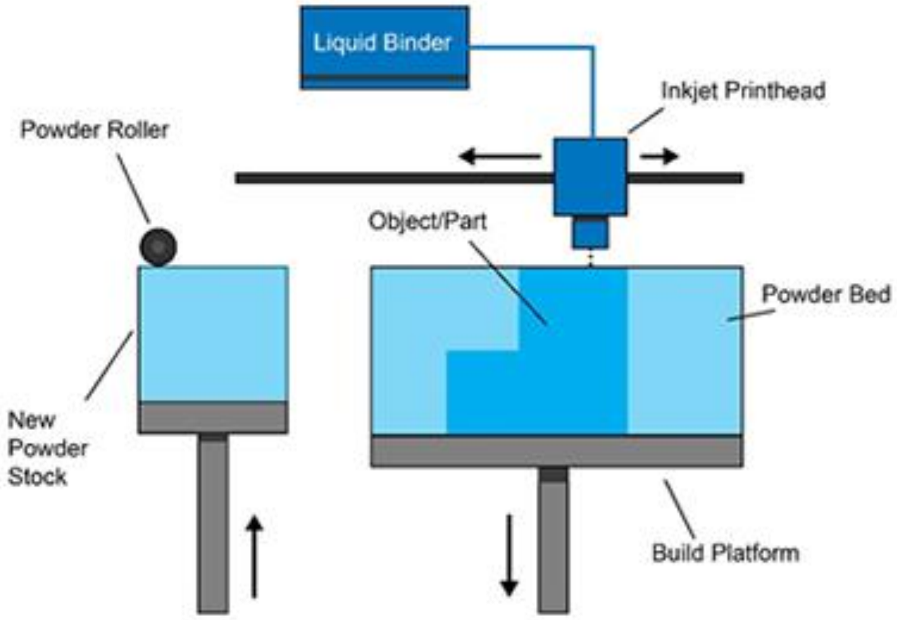

Figure 2: Binder Jetting (URL 2)

3.2.2 Directed Energy Deposition

Directed energy deposition is a sophisticated printing process. This printing process is commonly used when there is a need for repairing or adding additional material to existing components (Figure 3) (Tofail et al., 2018). Directed energy deposition could produce the good quality of the object and has high-level control of grain structure. As a principle, the process of directed energy deposition functions similarly to material extrusion, except that the nozzle can move in different directions as it is not fixed to a specific axis. Moreover, the process is mostly used with metals and metal-based hybrids. It can also be used with ceramics, polymers. Laser deposition and laser engineered net shaping are examples of this technology (LENS) (Tofail et al., 2018).

In this printing process, laser deposition technology emerged which has the capability of producing or repairing parts that have been measured in millimeter to meters. The technology of laser deposition is on increasing demand among various sectors as it is characterized by its ability of offering scalability and diversity. Examples of sectors includes transportation, aerospace, tooling and gas sector. During the casting, thermal energy can be exploited for melting, and parts can be completed subsequently (Shahrubudin et al., 2019).

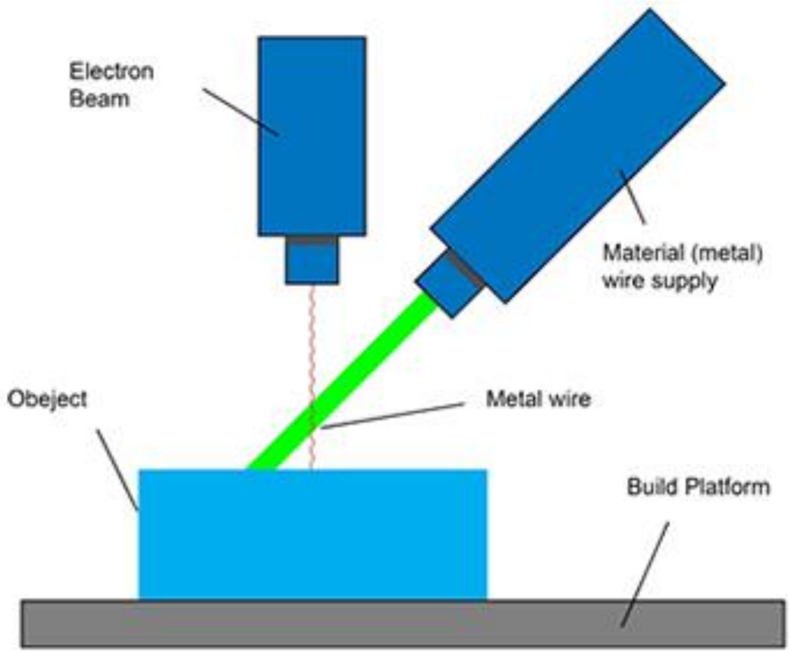

Figure 3: Directed Energy Deposition (URL 2)

3.2.3 Materials Extrusion

Material extrusion is based on 3D printing process that allows printing various colors and materials of food, living cells, or plastics (Shahrubudin et al., 2019). One or multiple material are added and extruded from a nuzzle by heating the materials to create an object layer by layer (Figure 4). The low costs of this process and its capability of building fully functional parts of the product made it broadly used (Shahrubudin et al., 2019). The first example of a material extrusion system would be fused deposition modeling (FDM) which started to exist in early 1990. The polymer is the main material used by this method (Stansbury & Idacavage, 2016). Moreover, FDM uses heating and extruding thermoplastic filament methods to build parts starting the layer process from the bottom to the top.

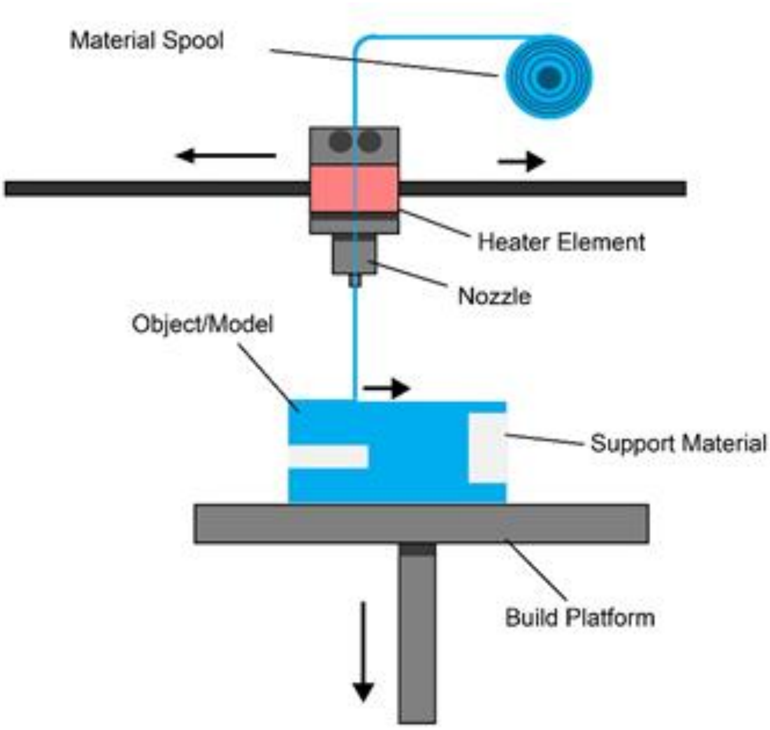

Figure 4: Material Extrusion (URL 2)

3.2.4 Materials Jetting

According to ASTM Standards, material jetting is a 3D printing process in which material must be deposited selectively in drops. In material jetting, droplets of photosensitive material are distributed from the print head, then these droplets of material solidify and make a part layer by layer under ultraviolet (UV) light (Figure 5)

(Shahrubudin et al., 2019). Moreover, parts created by material jetting are characterized by surface finish smoothness and high dimensional accuracy. The material jetting provides multiple material printing and different kinds of materials like hybrid, polymers, biologicals, composite, and ceramics (Tofail et al., 2018).

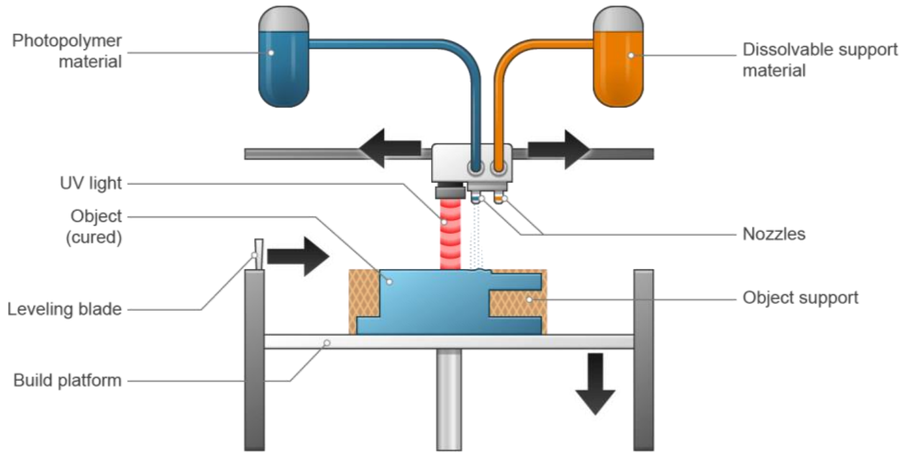

Figure 5: Material Jetting (URL 2)

3.2.5 Powder Bed Fusion

There are three printing techniques for powder bed fusion which are: electron beam melting (EBM), selective laser sintering (SLS) and selective heat sintering (SHS). The method used here with either electron beam or laser to fuse the material powder together (Figure 6). Materials used vary in this process from metals, ceramics, polymers, composite and also hybrid. Carl Deckard developed SLS technology in 1987. An example of powder-based 3D printing technology is selective laser sintering (SLS). SLS is 3D printing technology that functions in fast speed, has high accuracy, and also varies surface finish (Tiwari, Pande, Agrawal, & Bobade, 2015). In the process of creating plastic and objects that are made from ceramic and metal, selective laser sintering can be used (Lee Ventola, 2014). To generate a 3D product, polymer powders are sintered by a high power in SLS. Meanwhile, SHS technology can be used as a head thermal print as a part of 3D printing technology to melt the thermoplastic powder to create 3D printed object. Lastly, electron beam melting is used to enhance the energy source in the process to heat up material (Lee Ventola, 2014).

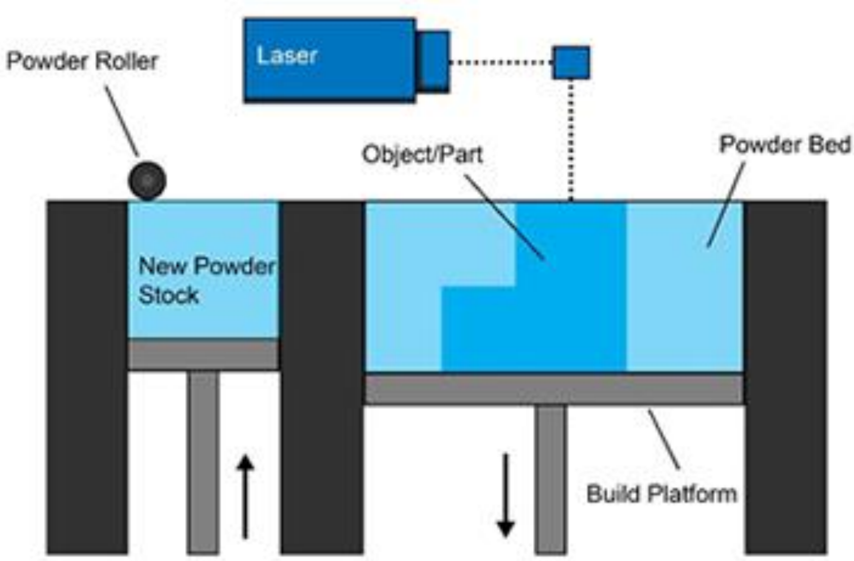

Figure 6: Powder Bed Fusion (URL 2)

3.2.6 Sheet Lamination

According to ASTM definition, the 3D printing process in which sheet of materials are bond together to create a part of object is called sheet lamination (Silbernagel, 2018). There are two examples of 3D printing technology that often uses this process, are laminated object manufacturing (LOM) and ultrasound additive manufacturing (UAM) (Tofail et al., 2018). In this process the material moves to the printing platform then a mirror reflects laser into the material to create the object, then the extra materials move to a material spool (Figure 7). Sheet lamination process has many advantages, such as it can do full-color prints, it's relatively inexpensive, excess material can be recycled and easy to handle material. Laminated object manufacturing (LOM) is used to manufacture complex geometrical shaped parts. Also (LOM) parts manufacturing is lower in fabrication cost and less operational time (Vijayavenkataraman, Fuh, & Lu, 2017). The use of sound to transform layers of metal from featureless foil stock, is called ultrasound additive manufacturing (UAM).

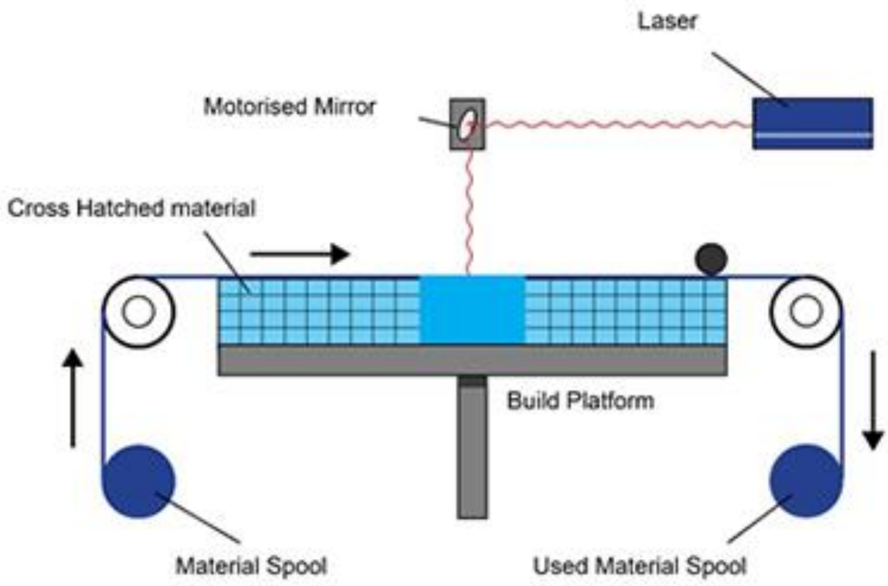

Figure 7: Sheet Lamination (URL 2)

3.2.7 Vat Photopolymerization

Photopolymerization is the most frequent 3D printing technology used, which also known as photo-reactive polymers by using a laser, ultraviolet (UV), or light (Low et al., 2017a). Digital light processing (DLP) and stereolithography (SLA) are examples done by photopolymerization. The technique in the SLA was influenced by the irradiate exposure particular conditions and the photo initiator as well as pigments, any dyes or other added UV absorber materials (Figure 8) (Stansbury & Idacavage, 2016). Meanwhile, Digital Light Processing and Stereolithography are two similar processes which work with photopolymers. A light source in this manner create major difference. A liquid crystal display with an arc lamp is a more conventional method used in the Digital Light Process. A full coverage of photopolymer resin to the entire surface of the vat in can be applied in a solitary pass, for the most part making it quicker than Stereolithography (Reddy, 2016). Vat Photopolymerization has very important parameters which are the wavelength, the amount of power supply, and time of exposure. The materials which initially used in this process come in liquid form and by exposing the materials to ultraviolet light, the material harden. Photopolymerization is suitable to achieve a premium high quality and good detailed product (Shahrubudin et al., 2019).

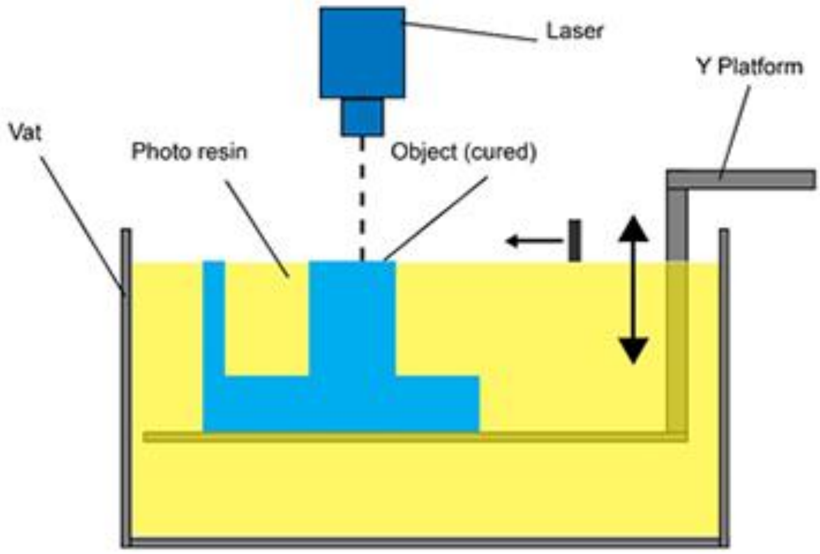

Figure 8: Vet Photopolymerization (URL 2)

3.3 The Applications of 3D Printing in Manufacturing Technology

3.3.1 Aerospace Industry

One of the 3D printing advantages is its ability to offer unlimited design options in materials and production. 3D printing can improve the aerospace industry, as it can reduce energy requirements and materials by creating lighter parts (Joshi & Sheikh, 2015). As a result, fuel consuming can be reduced by using 3D printing technology. This technology has been also used a lot in creating aerospace replacement parts like engines parts (Figure 9). Therefore, 3D printing technology participated in solving the issue of the constant need of engine replacement as it can be easily ruined. (Singamneni et al., 2019). In aerospace industry, it is preferable to use materials that resist corrosion, made of stretchy components such as nickel-based alloys (Uriondo, Esperon-Miguez, & Perinpanayagam, 2015).

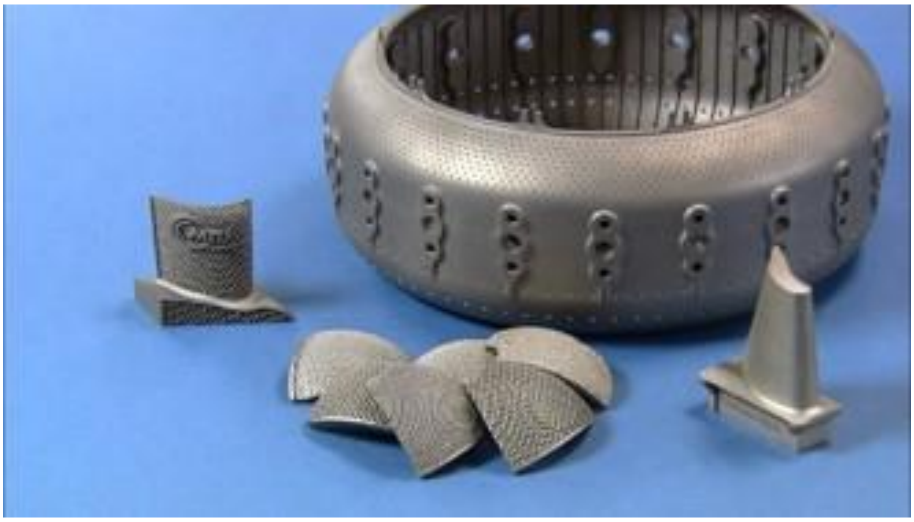

Figure 9: Airplane Engine Parts (URL 3)

3.3.2 Automotive Industry

In fact, 3D printing technology has made a positive change in different industries, as it has developed new things in design. 3D printing has made a progress in automotive industry as it enables lighter and more complexity of structures speedily. The first 3D-printed electric car was printed by local Motors in year 2014 (Figure 10). Local Motors has also benefit from the various usage of 3D technology and printed a 3D bus that was named OLLI. OLLI is a self-driving vehicle that can be recycled. It is also considered extremely smart.

Moreover, one of the most company's using 3 D printing technology is the well-known Ford. Ford has used this technology to create prototype and parts of engine (Sreehitha, 2017). Furthermore, 3D printing technology was also used by BMW in hand tools production for the purpose of automotive examining and collecting. At the same time in 2017, there was a collaboration between AUDI and SLM Solution Group AG to create preliminary versions and replacement parts. (Petch, 2018). Therefore, 3D printing technology made it easier for automotive industry to have various selections. It has also highlighted the importance of the progression phase to achieve ideal automotive design. Concurrently, waste and materials consumed can be reduced by using 3D printing technology. Moreover, it enables examining a new design in quick time due to its ability to lower the cost and time.(Sarvankar & Yewale, 2014).

Figure 10: The first 3D Printed Electric Car (URL 4)

3.3.3 Food Industry

3D printing has also played a significant role in food industry. Nowadays, the demand for developing customized foods to meet customer's particular needs is increasing. For example, customized food for athletes, children, pregnant woman, and patient.

Therefore, the amount of unnecessary ingredients needs to be reduced in this type of food as it needs to be made from healthier ingredients. (Low et al., 2017b). Here comes the significant role of using 3D food printing technology, as the process of customized food development needs to proceed in a complex and effective way. 3D food printing also known as food layer manufacture is a new method of producing food digitally which is being used recently. In this process a food product is derived and designed with computer aided design by deposing layer by layer. (L. Liu, Meng, Dai, Chen, & Zhu, 2019). Using 3D printing technology allows mixing certain materials as well as processing them into different textures and shapes (Z. Liu, Zhang, Bhandari, & Wang, 2017). Types of new food can be produced in complex and appealing way by using various kinds of food items including, sugar, chocolate, pureed food and flat food such as pasta and pizza (Figure 11). 3D printing is considered a highly efficient technology in food production. In addition, 3D printing is eco- friendly technology that provides good process control, and costs less. Furthermore, 3D food printing is adjustable to the consumers' preferences and needs. It has developed a new technique for customized food. It gives the potential to have diets by making food ingredients be automatically set to the consumer's preference (L. Liu et al., 2019).

Figure 11: 3D Print of Food (URL 5)

3.3.4 Healthcare and Medical Industry

3D printing technology can be used to print various medical related objects, such as drug and pharmaceutical research (Aho et al., 2019), organ and skin (Lee Ventola, 2014), and replacement tissues (Y. Liu, Hamid, Snyder, Wang, & Sun, 2016). It is also able to print cartilage and bone (De Mori, Fernández, Blunn, Tozzi, & Roldo, 2018), and it helps in cancer research (Knowlton, Onal, Yu, Zhao, & Tasoglu, 2015). 3D printing can be used to create models for education, visualization, and communication. 3D printing technology has many advantages in the medical and health sector which are:

• The natural structure of the skin can be reproduced by the use of 3D printing technology and with lower price. There are many usages and needs of the 3D printed skin such as testing cosmetic, pharmaceutical, and chemical products instead of using animal skin, resulting in reaching results that are more accurate (Yan et al., 2018).

• 3D printing technology enables increasing the preparation of drugs. Moreover, drugs size and dose can be much controlled, by using this technology (Lee Ventola, 2014).

• 3D printing capability of printing cartilage and bone (Figure 12) for the purpose of bony voids replacement in the cartilage (Bogue, 2013). The difference between this type of treatment and other types of treatments such as using auto-grafts and allografts treatment is that, generating, keeping and improving the bone by the use of vivo is given priority.

• Replacing tissues is also one of the tasks that 3D printing technology can do. In addition to its ability of restoring, maintaining and improving the function of the tissues. The 3D printed replacement tissues are characterized by being not harmful to living tissue and having interconnected pore network. Moreover, the surface chemistry of these 3D printed tissues are appropriate in addition to its good mechanical characteristics.(Y. Liu et al., 2016).

• 3D printing technology is also able to print organs which are needed when there is organ failure due to disease, accidents, and birth defects.

• 3D printing technology has also shown positive impact in speeding cancer research as it can be used to form controllable cancer tissues model. Therefore, patients are able to get data that is more accurate and credible by using 3D printing technology.

• 3D printing technology has helped in and developed the learning process. Neurosurgeons can use 3D printout models to practice surgical techniques. Accuracy can be improved by using 3D model in such cases. Moreover, trainer can take less time to finish clinical procedure by using 3D model. 3D model has also made hands on training possible for surgeons.

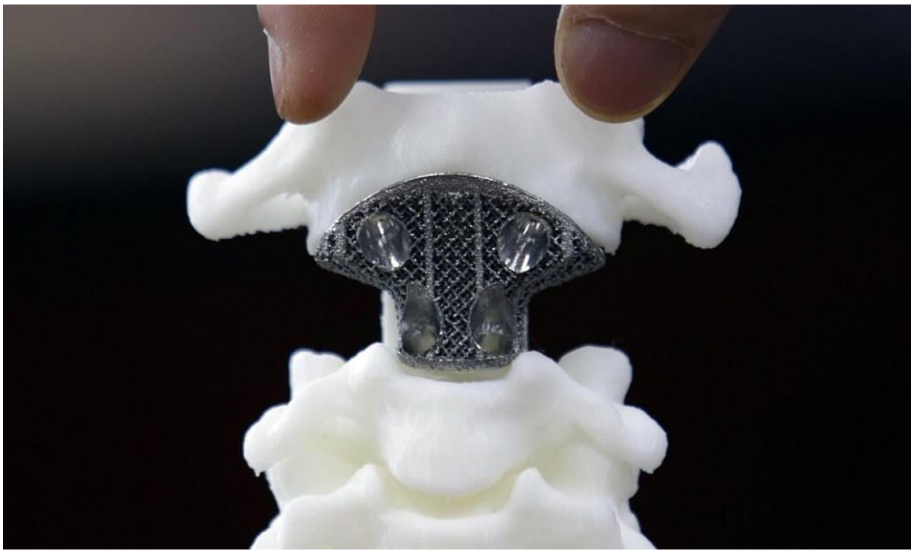

Figure 12: 3D Printing Human Bone (URL 6)

3.3.5 Fabric and Fashion Industry

3D printing technology has also entered the retail industry. Therefore, printed shoes and jewelers started to emerge (Shahrubudin et al., 2019).3D printing technology is also used to print clothing and consumer goods (Gaget, 2018). 3D printed fashion is spreading all over the world despite the fact that it may not appear naturally fit. Nike, New Balance and Adidas are ones of the big and well-known companies who are making a great effort to develop the huge production of 3D printed shoes. Adidas has 3D printed shoes for athletes (Figure 13) which got attention world-wide. 3D printing technology is used to produce different types of shoes, for example athlete's shoes, and shoes that are made to a particular customer's order (Horaczek, 2018).

Figure 13: 3D Printed Shoes by Adidas (URL 7)

In addition, more creative possibilities in fashion design can be achieved by using 3D printing technology as creating shapes without requiring moulds became possible by applying this technology. 3D printing technology can create and design clothing following the mesh system in fashion industry. The use of 3D printing technology is not only applied in fashion industry for printing clothing, it can be also applied to print leather goods and accessories such as jewelry and watchmaking (Amandine, 2018). The goal of using 3D printing technology in fashion industry is believed to be improving, developing and providing unique products design that meet the customer's specific order. This is what most retailers and designers believe in rather than being used just for repeating and recreating existing products (Vanderploeg, Lee, & Mamp, 2017). What characterized a 3D printed product is that it meets the customer's fit and style. Moreover, reducing the cost of supply chain and delivering products in small amounts in faster time are attainable by the application of 3D printing technology (Attaran, 2017).

3.3.6 Electric and Electronic Industry

3D printing technology is becoming more able to be reached and used in various industries, technology and sciences. Thus, manufacturers started to notice 3D printing technology's great capabilities. For the time being, there are many technologies of 3D printing that have been applied widely in structural electronic devices. For example, materials that are electronically active and electrode. Moreover, it can be used for devices with mass customization and adaptive design by connecting the conductors into devices that are 3D printed (Lee, Kim, Choi, & Lee, 2017).

One of the advantages of producing 3D electrode is that it costs less and takes less time for electrode materials producing. Unlike aluminum, copper and carbon electrodes which considered commercial, the 3D electrode' surface and design are able to be modified in order to meet a specific application. Moreover, printing 3D electrode is a completely automated process. The process itself is characterized by high degree of accuracy. Thus printing process for eight electrodes can be done in just 30 minutes. (Foo, Lim, Mahdi, Wahid, & Huang, 2018). Another advantage of this technique is that a circuit board can be modeled and formed to fit the shape of the product (Figure 14). The ability to design and form a circuit board for a compact space improves material and space efficiency.

Any component or electronic device that can amplify and manage the electric flow charge is considered active electronic component. Moreover, devices that are capable of generating power are also active devices. There are many examples of active electronic components such as transistors, silicon-controlled rectifiers, operational amplifiers, diodes, batteries, light-emitting diodes (LEDs) etc. These components have complex operations in comparison to passive components, therefore a detailed manufacturing process is required (Saengchairat, Tran, & Chua, 2017). 3D printing technology has not only positively affected the processing of product itself but also the electronics accompanying the product. In Industry revolution 4.0, adopting electronic system can be possible for multi-material printing technology. This will allow to create more innovative designs by using one process. (Baldassarre & Ricciardi, 2017).Today, there is an urgent need for developing a green electronic device in order to handle environment pollutions. Moreover, this green electronic device has to be safe, extremely reliable, and have low cost. (Foo et al., 2018).

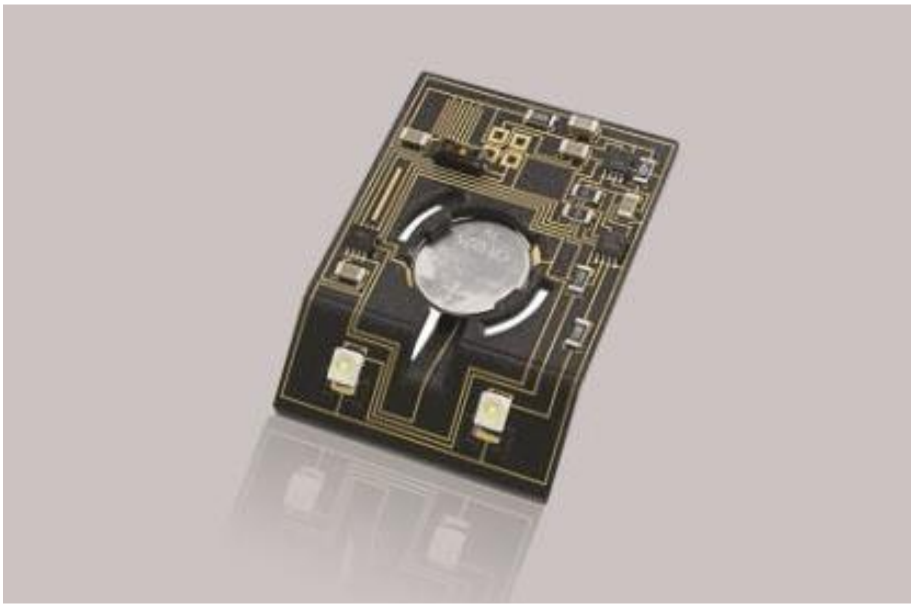

Figure 14: 3D Printed Circuit Board (URL 8)

3.4 The Use of 3D Printing in Architecture and Construction Industry

3D printing technology is also called additive manufacturing (AM). 3D printing technology is eco and it is known for its ability of providing unlimited possibilities to achieve organic geometric complexity. The use of 3D printing technology can be seen in the construction industry such as printing a whole building or producing construction components (Figure 15,16). There are two ages in Architecture, Pre-Industrial Revolution and Post-Industrial Revolution. In Pre-Industrial Revolution buildings ware distinctive and were able to be modified but constructing buildings process was slow. In Post-Industrial Revolution the constructing process became faster, but buildings were no more unique and lost their ability to be modified. This gap between huge production and customizability can be bridged by using 3D printing.

Figure 15: 3D Printing Entire Building (URL 9)

The process of manufacturing that follows layer by layer technique in 3D printing provides wide range of designs and freedom. One of the 3D printing applications expectations is that the possibility of using it to produce sophisticated structures such as acoustic damping wall element, doubly curved cladding panels, or other components that have irregular complex organic shapes. Additive manufacturing gave advantages to architects as it made producing interior and exterior geometries with higher degree of complexity easier and less costly for them compared to conventional construction processes. AM gave architects the ability to look at and consider their design and forms differently. Moreover, it gave them more space of freedom taking in consideration keeping complexity and the output (Khoshnevis, 2004). Adding operation, reducing weight and improving structure are now possible by following manufacturing process which can produce any kind of geometry components.

By using 3D printing, architects are able to focus on building functionality and have more freedom designing the building form without being as much as worry about the construction of the forms. For example most of the concrete designs in conventional construction techniques, are created according to the constructing ability. (Delgado Camacho et al., 2018a).

Figure 16: 3D Printing Building Elements (URL 10)

3D technology has been adapted and supported by many companies, one of these is the National Aeronautics and Space Administration (NASA) (Litaker et al., 2013). As the prosses of sending astronauts to space is not simple and takes time, NASA had the idea to use the 3D printing technology on Mars to build units. So far, there has been a test of Orion long-term manned spacecraft by NASA without human's crew. As it has been said by NASA, it may take up to nine months to travel to Mars. Astronauts who will be in that trip to explore the planet need a comfortable and sustainable shelter. Therefore, NASA made a competition that last for four years to design this "sustainable shelter" for the astronauts. SEArch+ cooperated with Apis Cor and proposed MARS X HOUSE, and they were rewarded the Virtual Construction Level 2 award of the competition for their MARS X HOUSE proposal (Figure 17) (Yashar, 2019). They created a design for five-storey building taking into consideration that the design includes comforts means for the astronauts. The design included four bedrooms, kitchen and Livingroom with Martian landscape views (Broom, 2019).

Figure 17: Mars X House (URL 11)

Moreover, MARSHA project which is a (Mars Habitat) was one of the most outstanding projects and it got awarded with first-place (Figure 18). It was created by New York company AI Spacefactory which is known for developing a 3D printed house for the purpose of living on Mars. The IA Spacefactory trying and hoping to develop 3D printed buildings on the surface of the red planet using existing materials on the planet (Michelle, 2018). This prosses encourage the sustainable development by avoid carrying materials from Earth.

Figure 18: MARSH by AI Spacefactory (URL 12)

To determine whether the building should be designed to be printed on site, on site under controlled temporary structure, or into building components off site in factory, the environment and the conditions of the site should be analyzed. There is a strong link between the buildings design and the surrounding environment conditions of the sites. In-site resources can be exploited for constructing buildings in where locative environment conditions are harsh (Cesaretti et al., 2014).The construction techniques, strategies, and materials are determined by environmental factors such as extreme winds existence, stability of the ground and other to ensure building constructions that are safe and able to be used. These factors dictate the construction system capabilities requires (Keating, Leland, Cai, & Oxman, 2017).

The use of 3D printing technology became better when Building Information Modelling (BIM) emerged. BIM is representing functional and physical characteristics digitally. Moreover, 3D building information can be shared. By integrating BIM, such as ArchiCAD, Revit, and Rhinoceros, with the 3D printing technology, the design prosses of the building and conception to demolition for construct will be more efficient. It also creates an efficient source for management and maintenance during the building life cycle (Sakin & Kiroglu, 2017). One of this cooperative technology advantages is supporting more effective ways of designing and preserving the constructed environment. Now, companies are capable of designing the visual of the building by using 3D printing technology with low cost and in faster time. 3D printing technology enabled finishing projects on time and avoiding any delay. Adding to that, 3D printing technology facilitate better and more effective communication between construction-engineer and their clients. 3D printing technology made it easier and simpler for the customers to represent their ideas rather than the conventional methods such as paper and pencil (Hager, Golonka, & Putanowicz, 2016). Ones of the prominent examples of buildings that have been 3D printed are, 3D studio 2030, Office of the Future in Dubai, and Dubai Municipality Building.

3.5 Large Scale 3D Printer

Most of 3D printing devices are operating by using a robotic arm. The robotic arm is controlled by a special software system in order to control it. It is linked with the material storage system. The robotic arm is connected to the nozzle of the print. In addition, there is a pipe that connect the print nozzle with concrete mixer. Singapore Centre for 3D Printing (SC3DP) developed two kinds of printing devices; four-axis gantry and a six-axis robot arm. There are few more types of 3D printers which are delta system and D-shape System. Delta system and D-shape System, as they are still for research purposes, differ from systems that function like robotic arm and gantry system. However, robotic arm-based systems and gantry system are more developed and more used than the other two systems. Gantry systems and crane manufacturing apparatuses are similar in some aspects. The way that gantry systems can be transported with is like the transporting way of crane manufacturing apparatuses. In the printer, there is a rotating print head. This rotating print head can be placed in a single or multi nozzle. (Valente, Sibai, & Sambucci, 2019). Thus, these processes enabled for more geometric freedom without needing a formwork.

3D printing technologies are allowing for more accuracy, ability of repetition, higher resolution. In addition, more complex curved geometrical operations are achieved by using 3D printing technology. 3D printers are providing propositions and ideas that cannot be think of before. Fourteen 3D printers are available around the world. Some of these printers are fully functional, but some are still in the development process (Table 2) (Cherdo, 2019). The following table (Table 2) compares the large-scale 3D printers according to their availability, type, building size (capability), and location. The focus in this study is highly on the robotic arm system and gantry system as they are commercially available and have been used in the construction process of the selected cases.

Table 2: Large Scale 3D Printers (URL 13)

3D Printer Name	Category	Type	Building Printer Size (m)	Location
BetAbram P1	Available	Gantry System	16x8.5x2.5	Slovenia
COBOD BOD2	Available	Gantry System	12x45x1.5	Denmark
Constructions-3D Constructor	Available	Robotic Arm	13 x 13 x 3.8	France
CyBe Construction CyBe RC 3Dp	Available	Robotic Arm	2.75 x 2.75 x 2.75	Netherlands
ICON Vulcan II	Available	Gantry System	2.6 x 8.5 x ∞	United States
Monolite UK	Research	D-shape System	-	United Kingdom
MudBots 3D Concrete Printer	Available	Gantry System	1.83 x 1.83 x 1.22	United States
Total Kustom StroyBot 6.2	Available	Gantry System	10 x 15 x 6	United States
WASP Crane WASP	Available	Delta System	Ø 6.3 x 3	Italy
Apis Cor	Project	Robotic Arm	8.5 x 1.6 x 1.5	Russia
Batiprint3D 3D printer	Project	Robotic Arm	Up to 7m high	France
S-Squared ARCS VVS NEPTUNE	Project	Gantry System	9.1 x 4.4 x ∞	United States
Contour Crafting	Service	Gantry System	-	United States
XtreeE	Service	Robotic Arm	-	France

3.5.1 Gantry System

The gantry is a system uses two parallel rails to be able to moves in horizontal axis (Figure 19). Those two rails are the first stage of assembling the system on site. The nozzle, which is attached to the top of the gantry, is designed to moves up and down. That help the system to be precise while extrusions and modeling and be able to work in different heights of the structure. The lintels and other construction materials are placed by a robotic arm located on top of the gantry system. The nozzle part of the system moves around to extrude the building walls. After the first layer completed, the nozzle automatically moves up to begin extruding the second layer on top of the first layer. The layer by layer prosses is repeated until the full height of the walls is completed. The layer by layer procedures are arranged by a task graph. The roof, lintels, window frames, pipes and other parts of the building are placed by a robotic arm.

Figure 19: Gantry System (URL 14)

3.5.2 Robotic Arm

In comparison to counter parts of gantry system, robotic arm systems are considered new. Robotic arm systems support the print nozzle by providing it with roll, pitch and yaw controls. This make the print nozzle more capable of carrying out more clear print designs such as following tangential continuity method to print (Gosselin et al., 2016). There are significant advantages provided by arm-based systems when using it construction tasks. It enables manufacturing complex structures such as doubly curved forms by providing high degree of kinematic flexibility. By using the tangential continuity method, transmission between print layers becomes smoother through keeping a continual rate of curvature change which gives more attractive and pleasant look. Moreover, arm systems allow accessing complex sites and make it simpler as the physical reach extent of the arm systems are very large.

A robotic arm system which is called Digital Construction Platform (DCP) was designed, built, and tested by Keating (Keating et al., 2017). The system is made up of hydraulic and electric robotic arms combined together. In order to fabricate printed structures on-site, robotic arm was installed on a driven movable platform. DCP's is a self-reliant system as its electrical drive system can be recharged by solar panels. Cybe RC 3D is another example of mounted robotic arm system (Figure 14) (CyBe, 2018). In Cybe, there are 6-axis robotic arm installed on the tracks of a caterpillar. It is the system that is being used in the process of 3D printing the R&Drone Laboratory which is located in Dubai (Saunders, 2017).

Figure 20: Robotic Arm (URL 15)

3.5.3 Delta System

Delta system is also a large-scale 3D printer. WASP which is a 3D printer developer has created "Big Delta". Big Delta is a 12-meter-high 3D printer designed for house manufacturing (Lu, Song, Wang, & Chen, 2019). Technology has been led by researcher to be designed and implemented through types of apparatuses, which are the WASP “Crane” and the WASP “Big Delta” printer. The configuration of “Big Delta” is 12 meter in high and 7-meter in wide and attached to it 6-meter modular arms (Figure 21). To make it easier to load and transport, the Big Delta component designed to have a maximum length of 3 meter (Valente et al., 2019). Delta robots are known for their high in accuracy, low moving inertia, and advantages in high stiffness as printer structure, which make them attractive for the industry. To follow the targets of

WASP technology, the printing nozzle in Delta system is suitable for mixtures which are containing long-fiber materials. The improved straw with synthetic or natural fillers and raw terrain are the base for the construction materials extrusion.

Figure 21: Delta System (URL 16)

3.5.4 D-Shape System

D-shape is one of the largest 3D printers in which sand and magnesium-based binder are bind together selectively layer by layer to create objects like stones. There are spreading nozzles in the print head which deposit a liquid after spreading out the powder material to the required thickness. Sand is bind together through this binding liquid selectively based on digital prototypes. At the same time, the remaining sand can be used in enhancing the structure. The printed object is taken out of unconsolidated material after completing the printing process. The printer can reuse the rest of the powder in other manufacture process (Lim et al., 2012). What characterizes the D-shape printer is the printer head that is equipped with spraying nozzles. There is a horizontal beam that connect the square base with the printer head. The horizontal beam can move along X-axis freely. Four stepper motors attached to the vertical beams move the square base vertically Z-axis (Figure 22). During the printing process, a binding liquid is selectively sprayed on areas of the sand layer that has been predetermined. When printing a layer is completed a horizontal beam can also be used to spread powder material before fabricating the subsequent layer (Cesaretti et al., 2014).

The effectiveness of D-shape has been shown and proven in the printing process of large structures. D-shape has been used to create a freeform with a 1.6 m high. Moreover, it allowed to build an entire house in only one printing process (Fonda, 2013). The European Space Agency (ESA) has funded a research projects that have succeeded in using 3D-shape to print complete scale components for the lunar base accompanied artificial moon dust. However, the way the printer operate on the moon and its environment has been tested as well (Cesaretti et al., 2014). Moreover, D-shape may also be useful in military as it has been claimed that it will enable constructing infrastructure such as hospitals, bases and bunkers. And it will take less time compared to the time it would take when following traditional methods (Adlughmin, 2014). Enrico Dini and a collaborator Vittadello had the intention to use D-shape printer to print various structural blocks. The material's components were sand, salt and an inorganic binding agent. Machines were used to assembly blocks in order to form the future look of structure (Adlughmin, 2015).

Figure 22: D-shape System (URL 17)

3.6 Materials

3D printing has different requirements as any building process. An important requirement for 3D printing in order to build and preform consistently is high quality materials. For that reason, material requirement procedures should be agreed by providers, buyers, and consumer of the material. 3D printing technology is able to produce fully functional buildings or building parts from range of materials such as adobe, concrete, metal, and timber. Moreover, it can produce 3D printed object by using ceramics and concrete without it being cracked, thus 3D printing technology has contributed in facilitating and improving the construction work (Shahrubudin et al., 2019).

The cement mixtures must contain proper compositional properties and rheological to improve the deposition procedure (Valente, Sibai, & Sambucci, 2019). The excellent physical properties are what characterize the material (Shahbudin et al., 2019). Even though this study focuses on the use of 3D concrete printing (3DCP), the other materials used in the technology are important and played big role in developing it.

3.6.1 Adobe

There have been number of research studies about providing solutions for lower environmental impact and the ability to recycle the used material mixtures while applying materials that are based on earth or clay which can reduce the construction time. Adobe is an earth-based material which cost a few cents per kilogram only. Therefore, logically it is a perfect choice for 3D printing. Additionally, adobe's capability of being extruded often made it appropriate for controlled material deposition. The material is extruded in layer by layer method with an infinity like pattern to strengthen the structure of the form (Figure 23). 3DP techniques and earth-based material mixture have been used and applied in various projects. These projects range from small to large structures. Earth-based materials were subjected to an investigation in terms of their rheological and hardened properties. Moreover, a mixture of fine soil material with adding alginate seaweed were introduced in order to discuss the material's possibility to implement 3DP in construction industry (Perrot, Rangeard, & Courteille, 2018). Pylos project was introduced by the IAAC institute. In this project, an extruder was used in printing complex vertical elements off-site. The extruder used in this project deposited materials that are soil-based combined with natural biodegradable materials (Pylos, n.d.).

Figure 23: 3D Printing Adobe Structure (URL 18)

3.6.2 Concrete

3D concrete printing (3DCP) which is cement-based 3D printing process is being developed for the last 10 years. More than 30 groups in research studies were observed throughout the world (Buswell, Leal de Silva, Jones, & Dirrenberger, 2018). Currently, developing new materials that are suitable to be printed for concrete printing usage is the goal of the research at SC3DP. Materials such as fibre-reinforced mortar, geopolymer mortar, and lightweight mortar are examples of those suitable materials to be printed (Tay et al., 2017). Moreover, there are some materials that undergo tests such as rock powder or basalt, and aggregates of recycled glass in order to support construction sustainability. These materials went through several steps and analysis in order to examine and check their properties and appropriateness. In the previous stage of the study is devoted towards the machines "3D printers" used to 3D print concrete. Letter stage of this study describes the 3D printed concrete walls, its structure, and different methods. 3D concrete printer is able to provide value added which is one of its services. The value added can be provided through digital controlling of the building process and additional functionality design. The technology has been adapted to the architecture and building construction industry by printing building elements and full building using concrete as material (Martins & Sousa, 2014).

Figure 24: 3D Concrete Printing (URL 19)

The Ultra-High-Performance-Concrete (UHPC) is more developed concrete mixture to perform a higher strength (Figure 24). The UHPC is a fiber reinforced cementitious composite with a low water to cement ratio. The materials which are incorporating the UHPC are cement, supplemental cementitious materials which can be silica fume as well as some other materials, fine sand, steel fibers, superplasticizer, and water (Wille, Naaman, El-Tawil, & Parra-Montesinos, 2012). The use of UHPC along with 3D printing technology add a range of material shaping for its denser form.

3.6.3 Steel

The usage of additive manufacturing has extended also to small-scale steel parts constructing. There are small-scale steel parts that have been constructed by additive manufacturing in different industries for example, it has been used in aerospace industry to produce antenna brackets (Wiebke, n.d.), in energy industry to produce small-scale steel parts like molds for turbine wheel casting (Voxeljet, n.d.). Nevertheless, the advantages of applying 3D printing in steel on a wide range may be limited by circumstances such as printing duration and cost when considering larger scales. Steel material, that using powder bed fusion, is the least explored by construction companies for being small-scale applications. The small components made by powder bed fusion could show similar mechanical properties to some components that are done by conventionally manufacturing process, however; those components done by 3D printing are more expensive (Salomé, Sander, & Shibo, 2015). As it has been mentioned before, additive manufacturing has many advantages. And these advantages can be more apparent while constructing structures or components with complex geometries (organic).

The 3D metal printing (3DMP) in building construction sector has not been explored as much as other materials due to its initial cost expenses. A company called Arup investigated the 3DMP through a project to demonstrates the potential for developing and creating small scale structural metal components (Figure 25) (Delgado Camacho et al., 2018b). The development of stronger academic and industrial partnerships is substantial to encourage researches to recognize and evolve potential applications of 3D metal printing.

Figure 25: 3D Printed Steel Structure Joints (URL 20)

3.6.4 Timber

3DTP is a 3D printing process which uses a wood-based material. This process is used to produce wooden based components. A group of researchers from Swed`en's Chalmers University have demonstrated wood ultrastructure that is unique ("New Technology Promises To Create 3D Printed Wood Products," 2019). This technology could grow and improve the production of wood products. Moreover, this important development is based on a research that has been conducted earlier by a group. A wood pulp was converted into a nanocellulose gel in order to produce the ink for 3D printing. One of the benefits of 3DTP is the ability to combine timber waste with recycled plastics to create material which can be used to produce a high-performance construction element. A research at University of Sydney shows similar results. A team led by Professor Sandra Löschke who is the Director of the Architecture Design Research Group at the University of Sydney have been supported by the Forest and Wood Products Australia (FWPA) ("3D Printing Using Timber Waste Products," 2019). The 3D printing of timber involves the material to be placed through a nozzle and get applied to a surface layer by layer before it hardens.

3.7 Structure of 3D Concrete Printed Walls

To reiterate from the 3D Printing Section, walls that are 3D printed can have a horizontal truss system which give the walls the benefit of incorporate as structural walls. The corrugation between the inner and outer layers of the 3D printed wall, which act as horizontal trusses, gives 3D printed concrete walls higher load-bearing potential compared to traditional concrete walls. There is a notably large explosion of different 3D printing structural forms that still in progress. However, the most shapes that can be seen in standard reasonably priced housing project is corrugation (truss like pattern). To install the HVAC chases and electrical wiring the corrugation system should be broken and arranged differently in some parts of the walls (Zivkovic & Lok, n.d.). Similarly, some parts of the walls will not have corrugation for the structural columns and beams to support the roof. For those columns and beams, steel reinforcements are added to support the non-3D printed structural elements needed in the project. The exterior walls are penetrated to allow the structural elements to be placed. The way in which beams are allowed to puncture the exterior wall is formed on vigas method (Zivkovic & Lok, n.d.). It can also be formed on the wood beams of adobe architecture method that have also punctured the exterior walls in similar way.

Although there is a possibility of 3D printing concrete floor plates, cast-in-place concrete is determined to be more effective.

Because of the air gap created and the nature of the wall corrugation, the traditional wall insulation methods are less necessary for the 3D printed walls. Applying spray-foam insulation during the building process or installing attachable insulated wall panels are two promising methods of handing insulation. The spray-foam insulation could be achieved via a dual-nozzle extruder system, while one nozzle responsible for printing the concrete walls, the other nozzle would be spraying out the insulation. In some cases, pursuing sprayed foam insulation system is selected instead of the other method to express the details of the 3D printed wall, rather than a series of insulation panels hide the walls from the interior. 3D printer can take the place of the prevalent techniques used for building, such as puddled adobe, rammed earth, super adobe, and wattle and daub (Figure 26). Figure 26 shows the how 3D printing technology wall building methods, which are located on the right-side of the figure, can replace some conventional wall building methods on the left-side of the figure.

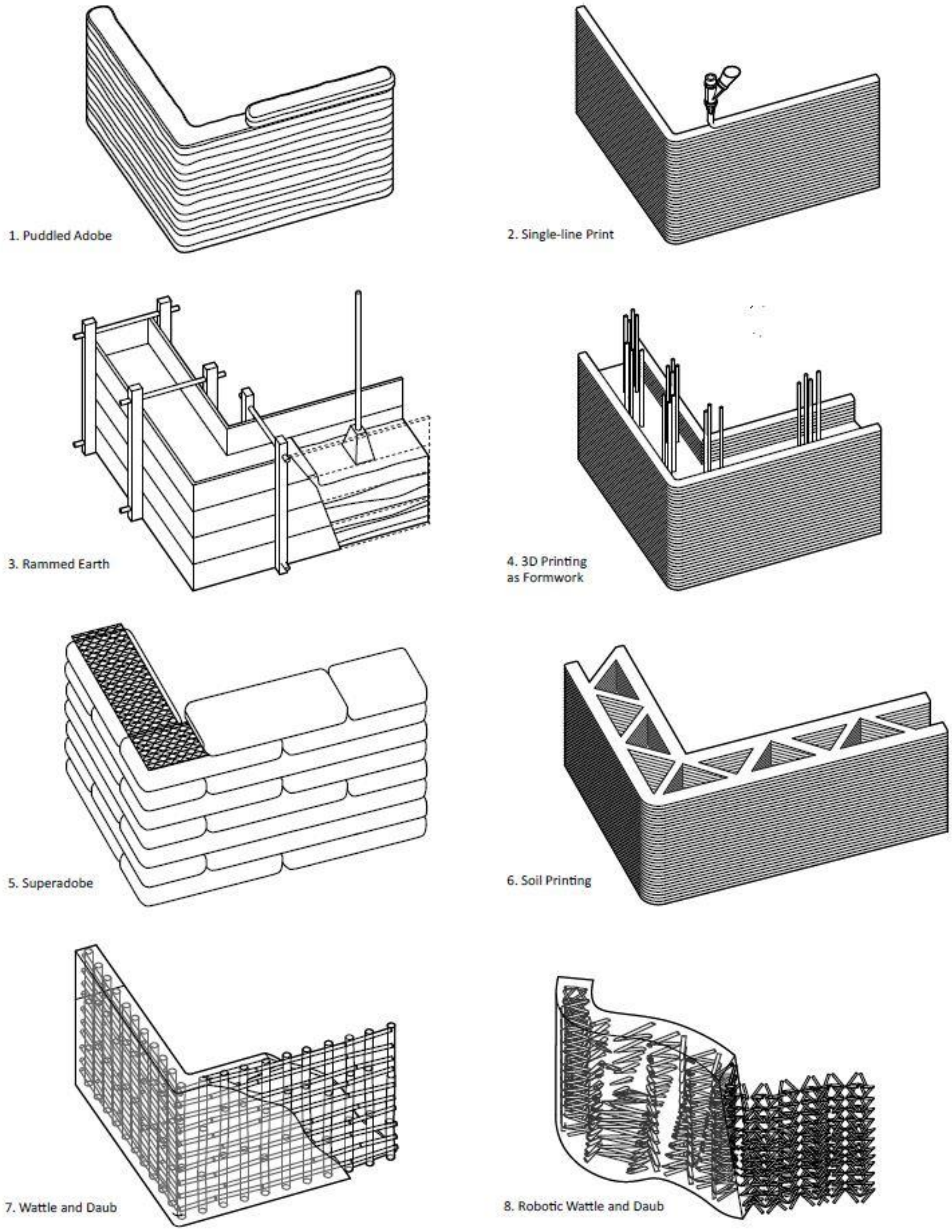

Figure 26: Diagram Comparing Common Building Techniques with Current 3D Printing Processes (URL 21)

3.8 3D Printed Concrete Structures

Nowadays, it is noticeable the increase of application of 3D printing world-wide as it has been used a lot recently in the building construction industry. There is many 3D printed concrete buildings around the world. Some of those buildings were constructed to test the potential of the technology, however; not many of those buildings are fully functional and being used. Nine of those buildings are the most known around the world, and they played a big role in improving the technology (Table 3).

Ones of the most effective 3D printing companies that have used the technology for long time are Apis Cor, CyBe, and Winsun. The Russian company Apis Cor has used this technology to build a 122 square meter house from zero in Moscow during just 24 hours (Table 3) (Sakin & Kiroglu, 2017). What makes the house remarkable and admirable is that it was built completely by mobile 3D printer only. The walls and this house's foundations were printed by using concrete mixture not only these but also other parts like windows, fixtures and parts that were added after construction such as furniture. Apis Cor joined Dubai Municipality and completed 3D printed two storeys structures which is considered the highest 3D printed structure (Table 2). The 3D printer was used to print the whole building on site through robotic arm using concrete as material. CyBe is a construction company located in Netherlands and work world-wide, also participated in the 3D printing technology. One of CyBe 3D printed projects is 3D Studio 2030 located in Saudi Arabia (Table 3). Winsun is a famous Chinese company that have completed building different sizes of buildings such as small houses and huge buildings and its services are available world-wide. In this company 3D printing technology has been used to complete many projects. One of the company's project that was 3D printed is the office of the future in Dubai. It was printed in their factory and then shipped to Dubai. The research studies and focuses on three cases which were selected according to their location, information availability, and material used (concrete) (Table 4).

Table 3: 3D Concrete Printed Buildings

Building	Photo	Location	Size (m^2)
Apartment Building by WinSun	 (URL 22)	Shanghai, China	1100
Apis Cor 3D Printed House in Russia	 (URL 23)	Moscow, Russia	73
Dubai Municipality Building by Apis Cor	 (URL 24)	Dubai, UAE	640
Office of the Future	 (URL 25)	Dubai, UAE	250

The Grand Piazza Cesare Beccaria 3D Printed House	 (URL 26)	Milan, Italy	100
3D Printed Mansion by WinSun	 (URL 27)	Shanghai, China	1100
3D Printed Tiny House in SXSW	 (URL 28)	Austin, TX, USA	60
3D Printed Hotel Suite by Andrey Rudenko	 (URL 29)	Philippines	131
3D Studio 2030 by CyBe	 (URL 30)	Riyadh, Saudi Arabia	80

3.9 Chapter Conclusion

Advanced manufacturing industry has witnessed a new, resilient and strongly efficient technique over the past few years which is 3D printing technology. It has been developing and improving in virus industries. The technology was able to serve various manufacturing sectors, such as aerospace, automotive, medical, fashion etc. The 3D printing technologies have reached far enough to be used in larger scale such as buildings construction industry. 3D Printing techniques allowed for more complex forms like curved structures, with lower cost, and less construction time. The fact that the technology could print almost any shape was an important factor for architects and engineers.

In building construction sector, the technology can 3D print a full building or can make complex curved geometrical building elements. In large scale 3D printing, the technology needs special machines and material. For that reason, researcher and developer have invested time and money to study and develop the 3D printers and material. 3D concrete printing technique is revealing signs indicating a future success. It is considered as revolutionary change in building and construction processes. The way we view and think of architectural buildings is changing especially with the emerge of largescale 3D concrete printing process.

Chapter 4

INTERPRETATION OF TECTONICS CHARACTERISTICS IN 3D PRINTED BUILDING

This chapter is divided into three sections. Firstly, the chapter will introduce the three selected cases. The second part will study and analyzes the cases according to their structures, tectonics characteristics, and sustainability. Finally, the 3D concrete printing technology in construction scale will be evaluated according to cost, time, and form arrangement.

4.1 3D Concrete Printed Cases Selected

As it has been stated before, there are many 3D concrete printed building around the world, however; this thesis will focus on three cases which have been selected according to their material, location, and information availability (Table 4). The material used in all three cases is concrete which is most common material used along with 3D printing technology for its liquid properties before drying. Also, concrete is known to be the most common material used in building construction because of its compression strength and durability. The cases are all located in the Middle East specifically in the Arabian Peninsula. The weather conditions of this region are known to be harsh. The high heat temperature can affect the construction prosses which shows more need for technology such 3D printing technology. The three selected cases are the most known and successful 3D printed concrete cases in this region which provide more information regard the buildings construction process.

4.1.1 Dubai Municipality Building by Apis Cor (Case A)

Apis Cor company has recently founded a new project in Dubai in collaboration with Dubai Municipality (Figure 27). It is basically a two-story building that was built by using 3D printer on site. Concrete was the material used by the 3D printer to build this structure. This project has allowed testing the equipment under harsh climatic conditions. Moreover, it has helped by conducting extensive research and development (R&D) to develop the 3D printing material and construction technologies. In returns, the 3D printer has succeeded in handling the harsh climate of United Arab Emirates. Dawoud Al Hajri, Director-General of the Dubai Municipality stated (Harrouk, 2019); " This project is a major turning point in the construction sector at the local and regional levels."

Figure 27: Dubai Municipality Building by Apis Cor (URL 24)

4.1.2 Office of the Future in Dubai (Case B)

United Arab Emirates National Committee founded the 3D printed office as the headquarter for the Dubai Futures Foundation (Figure 28). The "Office of the Future" built to serves as a meeting place for people from all over the world which are interested in the 3D printing technologies. It is a fully functional structure featuring water, electricity, air-conditioning systems, telecommunications, and 3D printing related objects. The 3D printed office was printed in China. The parts were shipped to Dubai after they have been printed. By using the 3D printing technology, the labor costs of the project ultimately reduced labor by 50 % to 80% and construction waste of the project by 30% to 60% (Sakin & Kiroglu, 2017). It is one of the motivational reasons behind the dominance of 3D printing in Dubai.

Figure 28: Office of The Future (URL 31)

The Office of the Future is the first fully functional 3D printed building world-wide that can be used which desined by Killa Design (Figure 29). An additive concrete layer creates a series of structural pods. The structure of the building was 3D printed where the foundation and the finishing materials were applied on site. The structure of the units was 3D printed inside a warehouse in China, which then they were transported to the site in Dubai. The 3D printer is a large printer called gantry system which is capable of printing of 36.5 x 12 x 6 meters structure. In fact, 7.6 meters is the average capability of most commercially available 3D printers. Nevertheless, it took 17 days to print all the structure, and couple months to install the HVAC and electrical systems and complete interior finishes. Nonetheless, the total cost was half the cost needed if the structure had been done by conventional construction method.

Figure 29: Office of The Future Front Façade (URL 25)

This project spots the light on one of the 3D printed construction criticisms. This is because Killa Design's main concern was noticed to be only on utilizing 3D printing for creating a shell to their project instead of focusing on making an effective use of the technology in interior finishes. Seemingly, Interior finishes were not on their priorities and were done by following traditional ways, which in result the project took more time to finish.

4.1.3 3D Studio 2030 by CyBe (Case C)

Saudi Arabia’s first 3D printed house has been built in Riyadh as it has been requested by The National Housing and Industrial Development and Logistics Program, aiming for more innovative building techniques (Figure 30) (Hamdan, 2018). The house is located on land of Housing Ministry and CyBe was the executed company for this project. To create a 3D digital model, layers are printed consecutively on top of each other till the final shape is formed. The house was built and finished in one week only.

This 3D Studio 2030 is following the ambitious goal and Vision 2030 set by Saudi government which is using more effective and new technologies such as 3D concrete printing and fast-brick robotics to build 1.5 million houses. It has been said by Majed bin Abdullah Al-Hogail the Housing Minister that this project will provide an insightful vision towards the construction future in Saudi Arabia and it will provide more job opportunities for its people by using modern technologies. As it has been said by the head of the program, Abed Al-Sadoon, one of the project's aims is encouraging the private sector to take advantages of technology in housing projects (Hamdan, 2018).

Figure 30: 3D Studio 2030 by CyBe (URL 30)

Table 4: Cases Information

Project	**Photo**	**Location**	**Size**	**Material**	**Printer Type**
Dubai Municipality Building	 (URL 24)	Dubai, UAE	2 floors high	Concrete	Robotic Arm
Office of the Future	 (URL 25)	Dubai, UAE	1 floor high	Concrete	Gantry System
3D Studio 2030 by CyBe	 (URL 30)	Riyadh, Saudi Arabia	1 floor high	Concrete	Robotic Arm

4.2 Cases Analysis

4.2.1 Construction Process and Structure of 3D Concrete Printing

There are few techniques that can be done using 3D concrete printing (3DCP) technology. The building prosses in each case is quite similar but still has some differences. The 3D printing method is selected according to many factors such as the building size and printer capability.

4.2.1.1 Case A

Dubai Municipality Building by Apis Cor was 3D printed on site facing the weather conditions unlike the rest of the cases. The foundation of the building was prepared before the arrival of the 3D printers. After the foundation have cured, the robotic arms were placed on top of the foundation. The building walls were printed using two robotic arms for the whole building. The interior and exterior layers of the walls are connected using the S shape pattern to create a stronger wall structure. This wall system is called hollow walls with corrugated internal structure. During the printing process, the robotic arms leave parts of the walls without corrugation according to the building structural elements “columns” dimensions, where the steel reinforcement is located (Figure 31).

Figure 31: Dubai Municipality Building Reinforcement (URL 32)

The steel reinforcement is spaced according to span (Figure 32). Later on, concrete mixture was poured around the reinforcement steel bars to create the building structure. That process eliminates the need for formwork. The 3D printed walls act as formwork for the concrete mixture which create an easier and cheaper method to apply a curved beam (Figure 33). Also, it creates strong bond between the building walls and structural elements.

Figure 32: Dubai Municipality Building Structure (URL 32)

The building slabs are precast concrete slabs (Figure 33). The reason to use precast concrete slabs is to reduce the construction time which is one of the aims of using 3D printing technology. The building beams were poured after placing the precast slabs. That form a strong connection between the building structure elements.

Figure 33: Dubai Municipality Building Slab (URL 33: Jasta, 2019)

4.2.1.2 Case B

The construction process of the office of the future in Dubai is different from the rest of the other cases. The building was printed in factory into sections, upper section of the building unites and lower section of the building unites. Again, in this case we can see the hollow walls with corrugated internal structure system, however; in this case we see the corrugation in the section of the building unites (Figure 34). That is because the building parts were printed on their side (Figure 36). This method was used to create curved connection between roof and walls, and between floor and walls (Figure 34). The curved corners filled with concrete mixture to create a stronger connection. The lower part of the structure includes the floor and half of the wall's height. The upper part of the structure includes the roof and the other half of the wall's height. The reason for using this method is to be able to ship the unites from China to UAE. After preparing the foundation, the lower parts of the structure (floor parts) were attached to the foundation. Then the upper parts got connected to the lower parts by screwing them together.

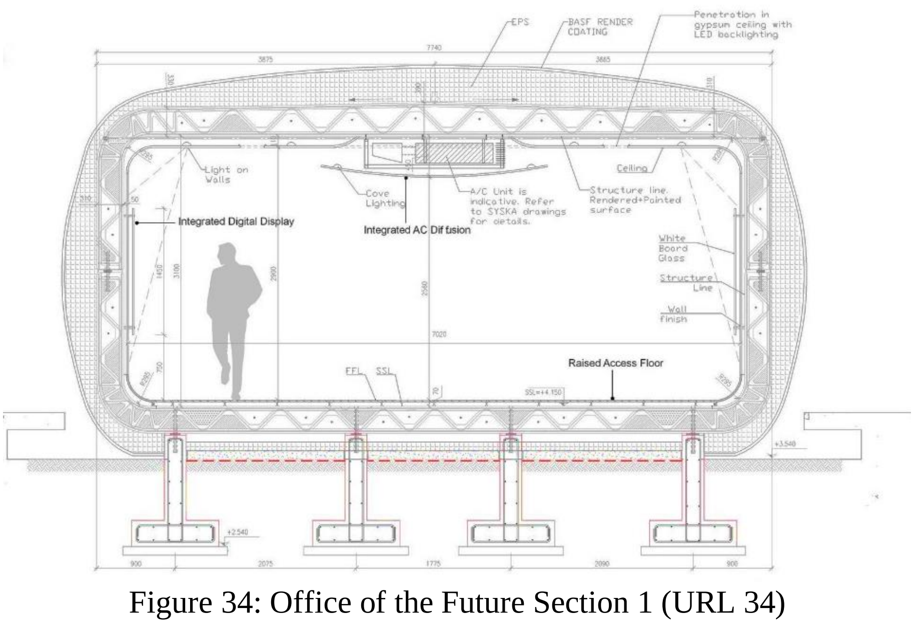

Figure 34: Office of the Future Section 1 (URL 34)

Later on, the water, electrical, and HVAC systems were applied. The building interior and exterior were covered using cladding material after adding the thermal insulation to the unites (Figure 35). A suspended ceiling used to hide the mechanical and electrical systems. Later on, all the furniture and fixtures were added to make the Office of the Future ready for public.

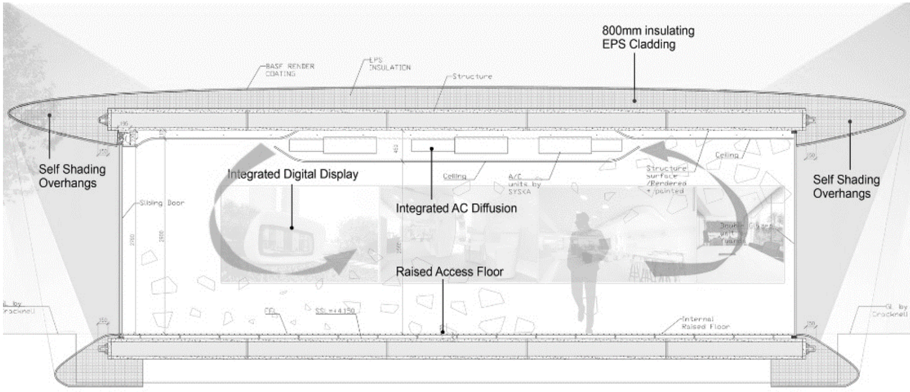

Figure 35: Office of the Future Section 2 (URL 34)

Figure 36: Office of the Future Parts (URL 35)

4.2.1.3 Case C

The construction method of 3D studio 2030 is slightly different form the rest of the cases. The prosses started by creating a foundation for the building to sit on. After that the robotic arm was placed on top of the foundation. In this case they used one robotic arm top print the walls of the building. The walls have been divided into sections so the robotic arm can print the full height of wall then move to the next part of the wall (Figure 37). This method was used because the maximum horizontal movement of the robotic arm used in this case is about 275 cm. during this prosses the 3D printer left the openings area empty for the door and windows to be installed later. The walls were divided into 27 sections and 21 parapets (Figure 38). The gaps between the walls, which is created by the wall by wall method, were filled to create a seal. Reinforcement was added previous to pouring the concrete mixture for the building beams and roof.

Figure 37: 3D Studio 2030 Wall Printing Process (URL 36)

The doors, windows and electricity sockets are placed during the printing process. In figure 38, the arrangement of building structural elements can be seen in red color, the walls in grey, windows in green, and doors in orange. That create a better understanding of the building components arrangement.

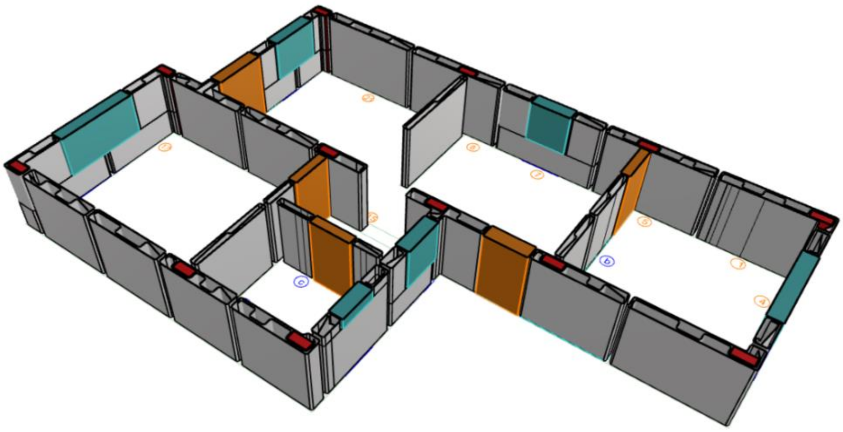

Figure 38: Walls, Columns, and Openings Arrangement Plan (URL 30)

4.2.2 Design Tectonics of 3D Concrete Printing

As some of 3D concrete printing techniques are different from the conventional building techniques and the possibility for creating curved forms, they can affect the tectonics of the building materials and forms. In this part of the analysis, the focus is on the design tectonics of the 3D concrete printed buildings. The cases are analyzed according to some design tectonic by observing the exterior and interior of each case through images and their tectonics criteria according to the tectonic theoretician.

4.2.2.1 Case A

The Municipality Building in Dubai is fully 3D printed out of concrete using robotic arm. The building exterior walls were painted white; however, the texture and makes that is left by the 3D printer can be seen on the building walls. The wall around the main entrance was left unpainted (Figure 27) to show the visitors that the building is 3D printed using concrete. That can be done to show that the Dubai Municipality is one of the first countries to use the technology specially that the building is the largest functional 3D printed building world-wide. Also, by reveling the 3D printed grayish color concrete structure creates a tectonic character to the building exterior. In this case the building looks similar to the traditional masonry structure unlike case B which looks unique and modern. The exterior has repetitive smaller openings unlike case B which has bigger openings. That make the characteristics of the municipality building is more stereotomic than tectonic. In this case Botticher would not consider the building artistic as he would in case B. The exterior of the building is more stereotomic as opposed to the interior of the building. The building is made from intersecting geometries that give it the montage character.

Figure 39: Dubai Municipality Conference Hall (URL 37)

The interior of the building is unlike the exterior, it has lots of tectonic value. The very smooth white walls, floor, ceiling, and furniture makes the interior spaces brighter (Figure 39, 40). The round walls in the conference hall gives the space futuristic look which adds tectonic value. The large curved screen which integrated with the wall also can give a modern futuristic appearance (Figure 39). The interior spaces are wide and no beams to be seen. The suspended ceiling used to cover the mechanical and electrical components to give the interior space cleaner look. That gives it the modern characteristic which also could be supported by Semper. Although the building seems that it does not have much openings on the façade, the interior spaces are well provided with natural light which is reflected by the reflective finishing material on the floor.

Figure 40: Dubai Municipality Meeting Room (URL 38)

4.2.2.2 Case B

By analyzing the exterior of Office of the Future, we can see the architectural tectonic values of the building. The building is covered (cladded) with smooth finishing material. Even though the building is solid, it does not feel heavy. The fact that it is elevated from the ground and its smooth curved walls (Figure 28, 29) gives a sense of lightness. Although it is a surface structure, it is not stereotomic but rather tectonics. The thin edges of the roof also support the lightness effect of the building. The smooth curved roof and the large sized openings on the façade create a futuristic appearance to the building. The rainwater treatment adds an architectural tectonic value to it. By eliminating the parapet wall, the rain water will leave marks on the sides of the building. That will make the building grow older and be part of the nature according to Hartoonian. The details of the building such as the hidden mullion of the openings, which we also can see in Church of the Light by Tadao Ando, add tectonic value to the building. According to Botticher, structure should represent art and in this case the structure is artistic. The outdoor stairs which are also thin and elevated from the ground give a futuristic look to the building and its surrounding.

Figure 41: Office of the Future Offices (URL 34)

The interior spaces of this case also have tectonic values. The connection treatment between the ceiling and the walls, which is one of adobe characteristics, is very smooth and there are no beams that gives light feeling. The lightness feeling is not common in concrete structure buildings and that shows that 3D printing can change the stereotomic characteristics of concrete. Despite the fact that the buildings appear light and small from the exterior, the interior spaces are quite large (Figure 41). Also leaving the 3D printed structure in front of the information desk (Figure 42) is considered a tectonic value. The light colors of the roof, walls, and furniture makes the interior space brighter and more spacious. Semper who promoted the modernity in materials and systems would support this case. However, the building structural joints are hidden under the finishing material which according to Semper building elements joints should not be covered because they are the ultimate design elements in architecture.

Figure 42: Office of the Future Entrance (URL 39)

4.2.2.3 Case C

The 3D Studio 2030 is a fully functional single floor detached house. The building exterior is painted white without adding plaster to the building walls. That was done to leave the horizontal pattern which is left by the layer by layer printing (Figure 43). The patterns give the building the characteristics of earth architecture “Puddled Adobe”. In this case the characteristics of the building is more stereotomic than tectonic. As the building has the characteristics of adobe, it appears to be modern but less futuristic, Botticher would not consider it artistic. The small openings of the building also support the stereotomic theory. The black windows frames which applied to create more modern appearance to the building can complement the façade.


Figure 43: 3D Studio 2030 Back Side by CyBe (URL 30)

The interior of the building reflects the exterior characteristics. In the interior of the building, the layer by layer texture can again be seen on the wall which can give a character to the interior. The joints between the walls are also perceivable. According to Semper joints are the ultimate design elements in architecture. Being able to observe the building elements joints allow us to understand the relation and connection between the building components. Even the layer by layer textures on both interior and exterior walls could be considered as joints which make the understanding of the building process easier (Figure 44). The suspended ceiling is used to cover the electrical system and to give the interior spaces cleaner look. The floor and ceiling finishing materials give the interior a modern appearance which Semper could be support it.

Figure 44: Interior of 3D Studio 2030 (URL 30)

4.2.2.4 Design Tectonic Criteria

The following table (Table 5) shows the results of design criteria of the cases according to structure representation of artistic value of structure, art of joint, montage and stereotomic by the tectonic theoretician Botticher, Semper, Hartonian, and Frampton.

Table 5: Design Tectonic Criteria Summary

	Buildings	Botticher Artistic Value of Structure	Semper Art of Joint	Hartoonian Montage	Frampton Stereotomic
1	Dubai Municipality Building	✕	✓	✓	✓
2	Office of the Future	✓	✕	✕	✕
3	3D Studio 2030	✕	✓	✕	✓

In the first case, the artistic value of structure of the building was not found. On the other hand, from the art of joint, montage, and stereotomic point of view were found. In contrast, the second case structure is artistic, but the rest of the design tectonic criteria were not found. In the third case, the design of the building was from the artistic value of structure and montage point of view are not found. Where the art of joint and stereotomic are found. That shows a variety of results that depend on the design tectonic of the buildings.

4.2.3 Sustainability Of 3D Concrete Printing

Nowadays, the sustainability of a new method and technology is an important issue due to the environmental and economic issues world-wide. The need for more sustainable building methods move the developer and researcher focus toward solving those issues. 3D concrete printing technology could solve those issues as it has many advantages, such as minimizing the pollution of environment, reduction of waste, decrease of injuries, and fatalities on construction sites could be listed. 35–60% of a concrete structure goes to formwork cost (American Society of Concrete Contractors, 2005). The reason for costing a large percentage of the construction process cost is due to the requirement of labor to assemble and disassemble the formwork. The use of formwork in case of complex curved geometries increases not only the construction cost, however it also increases the time required to produce the formwork which in result the overall time needed for the construction process unlike 3DCP which eliminates the need for formwork. In view of the fact that complex curved formwork is a special formwork designed for a special project, the formwork are used only once, that increases the waste (Delgado Camacho et al., 2018a). As the sustainability issue is an important factor in 3D printing and it can determine whether it is time and cost effective, the cost and time efficiency branch of sustainability are most to be mentioned.

In the Municipality Building in Dubai (Case A), by using robotic arm the building was fully 3D printed out of concrete. The entire building with all walls including its curved walls and structure was printed without using formworks. That reduces the cost of the building construction. The possibility to create any shape could easily be seen in the use of concrete because of its liquid properties before drying.

3D printed concrete produce obsolete, making it not a challenge anymore by the usage of formwork and complex curved forms. Making it more possible to achieve with a greater accuracy and also a smaller number of labors altogether with embodied energy. In that case 3D printed building offers new possibility for more sustainable construction in large scales. The project was done by only 15 workers which is half the usual number of construction workers needed in any other project (Carlota, 2019). Dawoud Al Hajri states; “ This will reduce construction costs and contribute to the development of solutions to demographic challenges by reducing the number of construction workers.”

Moreover, it reduced the amount of waste by 60 per cent. Obviously, 3D printing will play a significant role in the future of construction in Dubai. Emaar Properties has declared about its plan to build its first 3D printed home in Dubai back in July. It will collaborate with a contractor from UAE and international manufacturer of concrete 3D printer (Carlota, 2019). There was not more information and details from Emaar properties about the project. But this project opens the door for 3D printing to lead the construction future for this city as it will prove its effectiveness in developing construction industry. Moreover, the head of the UAE National Innovation Committee had announced a 3D printing target which is that by 2030, 25% of Dubai's buildings should be 3D printed (MacRae, 2016).

One of the advantages of using the technology in Office of the Future (Case B) is costs reduction from 50 % to 80% and construction waste from 30% to 60%. This what made 3D printing for construction desirable (MacRae, 2016). By reducing the material waste, in this case concrete, the cost of the building construction will be reduced in the other hand. Also, by reducing the use of concrete we decrease the carbon dioxide (CO_2) that is produced in the process of manufacturing concrete. The concrete material has many advantages, but it also has to deal with some difficulties. In fact, producing cement consumes a large amount of energy as a result of burning of slag in a kiln. Due to that, the process of producing cement is one of the causes of CO2 as it is responsible for 5% of the global CO2 output; World Business Council on Sustainable Development. Replacing cement by other materials such as fly-ash contributed in reducing CO2 output related to concrete production. However, the percentage is still high. In fact, the low costs of concrete raw materials make it difficult to reduce using it and therefore reducing CO2 is also difficult (Bos, Wolfs, Ahmed, & Salet, 2016).

4.3 Advantages and Evaluation

To evaluate the technology, first the advantages of the technology are listed as they play an important role in the time, cost, and curved forms issues. The advantages list will be followed by a table referring to the parameters which are cost, time, and form to evaluate the 3D concrete printing technology through the mentioned cases.

4.3.1 Advantages Of 3D Concrete Printing

There is a significant impact of 3D printing technologies such as AM on the construction industry. Therefore, there is many advantages which all revolve around cost and time reduction, and design complexity and flexibility.

4.3.1.1 Cost

It can be said that 3D concrete printing technology can be alternative technology to conventional methods. Since the 3D printing systems very recently using each day can be different applications parallel to technological improvements. That is why it is possible to say that 3D concrete printing technology can reduce building costs in many aspects, but of course, it is not easy to say that totally they are economic. The difference from conventional methods can be listed as; reducing time, less labor, fewer labor errors, or less material waste which are directly affecting the cost in the construction process.

3D concrete printing can remarkably accelerate the building process in terms of time cost. Allegedly, 3DCP process is time efficient. The initial cost of 3D printing depend on the country labor conditions and taxes as some countries require professionally trained labor where other countries do not require that. Traditional building processes take more than double the time taken by 3DCP process. One of the issues that may drive up costs is bad weather conditions which drive labor to stop working, however this will not be an issue for 3D printer. As regards material cost, the material used in 3D printing is waste material. Therefore the wastage percentage is almost zero which in returns also lower the cost (Fotheringham, 2016). 3D printing can decrease material consumption by accurately estimating the needed raw materials for objects fabrication before starting the printing process and by carefully depositing the material in the proper place while printing process. Moreover, labor cost could be reduced in the construction process as 3D printing is an automated process.

For example, Automated systems decrease human errors in the construction process resulting in reducing the material waste and needless work. Seemingly, 3D printing could decrease the labor cost and eliminates formwork requirement. In fact, formworks account for 35%–60% of the total costs of conventional concrete structures (Sakin & Kiroglu, 2017).

4.3.1.2 Labor

In order for labors to work in construction services, they must be trained before. Training labors takes time and money for that reason some construction companies tend to ignore the training needed which causes human errors. 3D printer can keep on operating till completing the task, whereas a laborer cannot work 24 hours a day. 3D printing reduced the number of labors needed to be on site significantly as it requires just the skilled ones (machine operators). As the 3D printing method is computerized and management oriented, it will open jobs opportunity for women to work as construction work and to take part in construction related activities.

4.3.1.3 Safety

Using 3D printers will reduce the number of injuries at construction sites by reducing the number of people required at site, and using machines to do most of the construction work.

4.3.1.4 Productivity

Convectional construction methods take from months to years to finish which is not the case for 3D printing method. The fact that 3D concrete printing method takes about three minutes to print one square meter, allows us to construct faster with few construction workers. Specially, in mass production 3D printing process can print a modest sized home in about 18 to 19 hours.

4.3.1.5 Flexibility in Form

The layer by layer manufacturing process of 3D printing unfold range of freedom for shaping materials (Figure 45), and creating complex structures is more efficient than ever before. It unveils for architects a greater freedom and flexibility in designing buildings and for civil and structure engineers the ability to produce and achieve various architectural geometries that were difficult or even not possible to achieve by the conventional methods.

Figure 45: 3D Printed Element (URL 40)

With 3D printing, architects and builders are given nearly absolute potentials for dealing with geometric complex constructions (Figure 46). Even though, 3D printing process has some limitations, it has ability for design freedom in construction and offers wide range of benefits for the largescale construction industry.


Figure 46: 3D Printed Structural Element (URL 41)

4.3.1.6 Possible Uses of 3D Printing in Emergency Housing

The term emergency housing is applied in this case to the use of 3D printing technology where shelters are necessary in short period of time due to wars, natural disasters, and pandemic issues around the world, millions of families are left displaced. Building can be destroyed within hours; however, it takes years to rebuild the area to be livable. In this circumstances water, food, and clothing are distributed to whom in need, but shelter is harder to provide and usually available in temporary forms such as tents and existing buildings. 3D concrete printing technology gives us the ability to build a house around 700 square meters with its plumbing and electrical systems in less than 24 hours (Fotheringham, 2016). The 3D concrete printing technology is an ideal option in this situation because of its time efficiency, low number of workers needed, and the potential of lowering the cost.

4.3.2 Evaluation

After identifying the cases and analyzing each case, in this part the cases evaluation is summarized in a table (Table 6). The cases were evaluated according to their cost, time, and any form. By evaluating the cases we could have a clear understanding of the 3D concrete printing (3DCP) technology in architecture and construction sector.

The literature and analysis done of the cases proved that the 3D concrete printing technology could improve the cost efficient due to its labor number required to construct a building; however, that depend on the county labor requirement. Also, the formwork in concrete structures is highly needed which acquire a high percentage of the construction cost, however, 3DCP do not require formwork. Due to the elimination of formwork cost in 3DCP, curved building forms and curved structural elements could be lower in cost. The technology has tended to reduce material waste which equally could reduce the cost of material needed for building construction.

In case of the time issue, 3DCP is known to be time efficient due to the ability to print 24 hours without stopping and without causing noises as much as the conventional construction processes. That make it beneficial in case of emergent housing. The time efficiency could help reducing the cost.

The 3D concrete printing (3DCP) is known to be able to achieve any geometry which changes the tectonics characteristics of the material. In fact, concrete is known to be one of the materials that we can achieve complex geometries with. Pairing concrete with the 3D printing technology improve that characteristic of the concrete material. Even though 3DCP technology has the ability to achieve highly complex geometries, it is not necessary to use it only in curved building forms. The following table, it summarizes the cases evaluation and categorize them according to their availability as an overall evaluation (Table 6).

Table 6: Evaluation

	Buildings	Location	Form Curvature	Cost	Time
1	Dubai Municipality Building	Dubai, United Arab Emirates	✓	✓	✓
2	Office of the Future	Dubai, United Arab Emirates	✓	✓	✓
3	3D Studio 2030 by CyBe	Riyadh, Saudi Arabia	✕	✓	✓

Chapter 5

CONCLUSION

According to the objective of the thesis, one of the benefactions of this thesis is to provide a clear understanding of the use of 3D printing technology in the architecture and construction industry. It is expected for the 3D printing technology to grow more in the near future. 3D printing technology was introduced to reduce time needed in prototyping manufacturing. Nowadays, the technology is contributing in many manufacturing processes. It is an alternative construction method attracting increasing attention. In fact, 3D printing technology has many benefits to the individuals, architects and engineers, and governments. Because of its promising applications, NASA has considered the technology to build shelters on Mars.

3D printing technology shows important advantages such as architectural design freedom, time reduction in general and in case of shelter mass production, and potential of cost reduction. The 3DCP method revolutionize the conventional building construction processes not only by reduction of labor needed for the construction process which decreases human error and injury risks during construction but also by having the possibility of producing building forms of almost any shape with potential of lower cost and time in some cases, and less waste which decreases the building footprint. In that sense, 3D concrete printing process has the potential to improve and reshape the manner in which we think about architecture and the built environment.

3D printed buildings are unique and contribute in the architecture aesthetics. The 3D concrete printing technology has proven to achieve architectural curved forms which contribute in affecting the tectonics of the building. The selected cases have shown variety of tectonic values. One of the tectonic values added by the technology is the lightness feeling of concrete which is not common in concrete buildings. The Office of the Future form shows that 3D concrete printing technique has the potential to change the stereotomic characteristics of concrete from heaviness look to lightness. Even though, concrete is known to be good in achieving different forms, such as shell forms; however, its high cost to create curved and different forms makes it economically inefficient. Another added value to the design tectonics is the layer by layer pattern on the façade, which is an earth architecture characteristic, that gives the building traditional look "Past" with new technology "Future" approach. The tectonics values that 3D printing adds can change and add to design tectonics.

It is time to develop and defined the future of architecture with the robotic systems. In the meanwhile, 3D printing can offer many advantages such as, time and cost reduction and the ability to create curved geometries, it cannot replace the conventional building methods completely. It is more likely to integrate both conventional and 3D printing method together in the future. The integration of the 3D printing technology with nano technology and smart materials is an important topic to be studied in for the future of architecture. The 3D printing technology is a wide topic; therefore, further studies regards the possibility for 3D printing technology to replace the conventional building construction methods is needed. This study could be suggested to undergraduate student as it is necessary to learn what could be the future of architecture and construction industry.

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