A ROADMAP TOWARDS ADOPTION OF 3D PRINTING IN CONSTRUCTION INDUSTRY OF DEVELOPING COUNTRIES

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THESIS ACCEPTANCE CERTIFICATE

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This thesis is dedicated to my parents and siblings for always being an unending source of love and encouragement.

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ABSTRACT

Pace of development and progress in construction industry of developing countries is very low as compared to developed countries. Use of automation in construction is inevitable for development of construction industry so that it can meet the housing and accommodation requirements of rapidly growing population. 3D Printing is one of the emerging automation technologies in construction. A plethora of research has been carried out to assess the current state of 3D printing in construction industry worldwide and to identify the key benefits and barriers towards adoption of 3D printing in building & construction industry. The study aims at developing a roadmap towards adoption of 3D Printing in construction industry of developing countries. A detailed survey is carried out to identify the key benefits and barriers towards adoption of 3D printing in construction industry. Customized designs, uniqueness in façade & reduction in construction time are identified as key benefits while key barriers are identified as lack of codes & guidelines and unavailability of suitable materials. A detailed data collection is performed for collection of a set of recommendations to optimize the effect of benefits and barriers. The recommendations from industry experts are used for development of a roadmap which will help in successful adoption of 3D printing in construction industry of developing countries. Continuous research & development, awareness campaigns & seminars and involvement on government level are suggested as the top strategies for successful adoption of 3D printing in construction.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

Three-Dimensional Printing	**3DP**
Additive Manufacturing	**AM**
Three-Dimensional Concrete Printing	**3DCP**
Program Evaluation and Review Technique	**PERT**
United Arab Emirates	**UAE**
United States	**US**
United Kingdom	**UK**
Literature Score	**LS**
Industry Score	**IS**
Survey Score	**SS**
Final Score	**FS**
Selective Laser Sintering	**SLS**
Stereolithography	**SLA**
Fused Deposition Modelling	**FDM**

Chapter 1

1. INTRODUCTION

1.1 Preamble

3D Printing or Additive manufacturing (AM), or Additive Construction is the most advanced and latest technology that transforms the Digital 3D Model to the real time products by printing them in layer. This technology is used for the real time construction / printing of the buildings and houses instead of making of 3D models only (Khorramshahi and Mokhtari 2017). The main advantages of this technology are increased efficiency, improved quality, more productivity and saving in terms of time and cost etc. 3D Printing technology is utilized in the industries like manufacturing, construction, automotive, health and surgical industry etc. 3D Printing in the construction industry is being adopted by the countries like China, UAE, US, UK etc. However, use of 3D Printing technology in industries of developing countries is still in its infancy. This research aims to pave way towards adoption of the 3D Printing technology in the building and construction industry of developing countries by proposing a roadmap towards adoption of 3DP through identification of challenges & opportunities. Introduction to the study is as follows:

1.2 Introduction

The world is quickly adopting the automation & other technologies in different fields as it saves time & money, is more efficient & productive, has higher level of accuracy & transparency, brings more comfort & ease to the every walk of life (Ferreira, *et al.*, 2018). More technologies are being invented & adopted quickly in the industries of developed countries (Lu, *et al.*, 2011). Developing countries are also trying to adopt these technologies slowly & gradually in different industries e.g. manufacturing industry, textile industries, agriculture etc. (Xue, *et al.*, 2018). Construction Industry is an important industry for every country as it contributes a lot in GDP of a country (Muroyama & Guyford, 1988). Construction Industry is moving towards achievement of fully automated construction projects especially in building construction through the use of the automation technologies like Robotics, 3D Printing, Augmented Reality and Virtual Reality etc. Technology adoption models for above mentioned technologies are being developed (Amer, *et al.*, 2017; Kangari, 1990; Li, *et al.*, 2018; Lu *et al.*, 2011). CI is developing day by day through application of the proposed models (Yamazaki, 2004). Construction of the mega projects (e.g. The Burj E Khalifa in Dubai, English Channel Tunnel which connects Southern England to Northern France etc.) wouldn't have been possible without adoption of modern-day technologies. Application of technology in the construction can help in meeting project objectives e.g. saving cost & time, keeping the quality of the product as per specifications & standards, reducing the production of construction waste etc. (Akmam *et al.*, 2018; Tatum & Asce, 2018a, 2018b). With the use of technology, projects can be designed and constructed within time, budget and as per standards and specifications.

3D printing or Additive Manufacturing (AM), is one of the above-mentioned modern-day technologies. 3D printing is a process that usually transforms digital three-dimensional models into real time products by printing them in layers(Panda, Tay et al. 2016, Panda, Tay et al. 2018). 3D printing has already been accepted as an established process in manufacturing, construction, healthcare, automotive, defense etc. (Panda, Tay et al. 2018).The use of large-scale 3D Printers as a tool for automation in building & construction has revolutionized the building construction process in the developed countries like China, USA and UAE etc. Anjum, Dongre et al. (2017)found that using 3D Printing as a tool for automated construction increases flexibility in the architectural design, lessens the labor dependency, saves time and money. However, the use of the 3D Printers in the construction and the building industry is comparatively limited & unsuccessful (Lu et al., 2011). This research aims to provide a roadmap toward adopting the 3D printing technology in the building and construction projects of developing countries. For this purpose, a thorough literature review was carried out to assess the use of 3D printing technology in the building and construction industry, availability of machinery, materials, and state of the art 3D printing technologies. Challenges and opportunities towards adoption of 3D printing in the building and construction industry were identified through literature review. Key challenges & opportunities in adoption of 3D printing in construction industry of developing countries, were identified through questionnaire-based surveys.Type-set questionnaire surveys and interviews were conducted from the industry professionals from developing countries. Respondents were asked to give their recommendations and opinions regarding identified challenges and benefit.Finally, a roadmap towards adoption of 3D printing in building construction through overcoming identified challenges & availing the opportunities, is proposed. The findings of this study will provide a baseline for adoption of 3D printing as an automation technology for building construction projects and will help professionals in meeting modern-day industry standards. Researchers can take this study as baseline for the future research in the area.

1.3 Problem Statement

Food and accommodation are basic psychological needs of humans but accommodation is still a problem especially in developing countries (Khorramshahi and Mokhtari 2017, Panda, Tay et al. 2018). However, construction industry is unable to meet the housing requirements of the rapidly growing population due to slow work progress, low productivity, cost & time overruns etc. Advance technologies are becoming integral part of construction industry & without adopting these technologies making progress in the field is not possible. Developed countries (e.g. China, Japan etc.) have managed to decrease the cost of designing and manufacturing the technologies like construction machinery to the extent that they are designing them as per requirement of the projects. However, in developing countries (e.g. Pakistan, Iran etc.), projects are designed keeping in view the availability of the technology owing to its much higher cost of acquiring the technology which is sometimes much higher than the cost of the project itself. Due to the reason, rate of development and innovation in construction industries of the country like ours is very low. Projects are being delayed, constructed on a higher cost and quality of construction is being compromised. Due to its lack of use and adoptability, our projects suffer cost and time overruns and the final product's quality is way poorer than what can be achieved through adoption of advanced technologies e.g. 3D Printing, in construction process.

1.4 Research Objectives

The objectives of the study are:

a) To identify the key challenges and opportunities towards adoption of 3D Printing in the building and construction projects of developing countries

b) To provide a roadmap for adoption of 3D Printing in the building construction projects of developing countries through overcoming the challenges and availing the opportunities.

1.5 Research Significance

Buildings are being printed at a faster pace and low cost as compared to conventional construction methods. This research aims to identify the challenges and barriers towards adoption of 3D printing technology. The final product of this study will be a proposed roadmap towards adoption of 3D printing in the construction and building industry of developing countries. Successful implementation of the 3D printing will lead to reduction in cost and time overruns in the construction projects of the developing countries. The study will also provide a cost and time comparison for the 3D printed and conventionally constructed buildings. Hence, it will make it easier for decision makers to decide whether to adopt 3D printing technology or not.

1.6 Research Scope

The primary scope of this study is limited to the application in the building and construction. However, many features may be interchangeable with other fields of civil engineering which are not in this study's scope. The 3D Printing is a future oriented construction technique which has the potential to affect the trends in housing and building construction industry. Proposed road map for the adoption of 3D Printing technology in building construction projects can be used by different organizations & professionals for the successful adoption of this technology in order to meet modern-day business requirements as per international standards.

1.7 Organization of Thesis

The first chapter of the dissertation is Introduction which includes overview, statement of problem, objectives of the research, research significance, research scope and study's organization. The second chapter, Literature Review comprises of a well-organized and thorough review of the available literature. In this chapter, different types of 3D printing technologies, machines and materials are discussed along with challenges and opportunities towards adoption of 3D printing identified during literature review. The third chapter explains Research Methodology that was adopted for this particular research. Tools for data collection, target populations and research limitations etc. will be discussed in this chapter. Results, analysis& roadmap towards adoption of 3D Printing will be discussed in the fourth chapter. The fifth chapter will comprise of conclusions, recommendations and academic significance of the study. The sixth and final chapter will be references.

Chapter 2

2. LITERATURE REVIEW

2.1 Background

Food and accommodation are the basic psychological needs of human beings according to the human necessities hierarchy of needs which was introduced by Maslow. Even in the 21st century, accommodation and housing conditions are one of the major problems in most of the societies. Different government and private organizations are trying their best to overcome this issue across the globe (Khorramshahi and Mokhtari 2017). Slow work progress, lower productivity, different construction methods, building management problem, wastage and high consumption of energy, increase in environmental damages due to over work of heavy machineries and high costs associated with traditional construction methods are some of the major concerns of the traditional construction methods (Panda, Tay et al. 2016, Khorramshahi and Mokhtari 2017, Tay, Panda et al. 2017). A significant portion of global GDP is contributed by the construction industry. Due to the lower profit margins of the construction industry, companies try to improve the productivity and the construction (Masera, Muscogiuri et al. 2017). There is a major shift in construction industry for the achievement of fully automated construction projects with use and application of emerging technologies like 3D printing, Robotics etc.(Anjum, Dongre et al. 2017). Such technologies have the potential to improve the productivity, efficiency, quality, safety, sustainability and quality as well as reduction in construction cost, time and construction waste (Ma and Wang 2018, Ma, Wang et al. 2018). Traditional construction techniques are going to be fully changed and / or replaced by the use of technologies (Wu, Wang et al. 2016, Wu, Zhao et al. 2018). The adoption of the 3D printing in the construction is urged by its success, effectiveness and advantages in manufacturing industry, education sector, healthcare, automotive industry etc(Panda, Tay et al. 2018). 3D Printing was found helpful in reducing the fixed cost & number of production cycles, in increasing the speed of production and balancing the supply and demand of spare parts, artificial human organs etc(Panda, Tay et al. 2018)

Three-Dimensional (3D) printing, or additive manufacturing (AM), is also known as rapid prototyping (Perkins and Skitmore 2015). In the mid 1990's, the use of the 3D printing in the construction industry was suggested. Initially deposition based and gantry-controlled printers were developed in that decade (Teymouri 2017). The use of cement-based materials in 3D printing was first suggested by Joseph Pegna in 1997 (Anjum, Dongre et al. 2017). Concrete printing, D-shape and contour crafting are newly developed techniques of the 3D printing. Companies like Apis core and Winsun have managed to print complete buildings in concrete by using these technologies (Anjum, Dongre et al. 2017). Ghaffar, Corker et al. (2018)suggested the 4 M's of 3D Printing namely Material, Making, Metrology and Market which include details about type & characteristics of material, printing process, qualities of 3D Printed objects and business opportunities of the 3D Printing. 3D Printing is an infant technological innovation in the construction industry (Panda, Tay et al. 2018). 3D Printing is the process that transforms 3D Models into real time printed objects by printing them in layers (Tay, Panda et al. 2017)usually the material is deposited in layers. Teymouri (2017) says it has the potential to revolutionize the construction by the invention of 3D Printers that can both justify their impact on both time and cost and deposit the material in layers. Anjum, Dongre et al. (2017)suggested that 3D printing helps in efficient planning, design customization and control over the construction environment. No doubt that Yeh and Chen (2018)recognized the potential of 3D printing to revolutionize the whole construction industry by integration of digital models of the projects to the real time construction. Traditional construction processes, materials and designs will be going through phenomenal changes once this technology becomes a norm in the building & construction industry(Wu, Zhao et al. 2018). With the progress of 3D printing in construction unnecessary involvement of human labor in dangerous tasks or activities can be eliminated. Application of this technology on real time projects can cause disruption or an end to the traditional and conservative construction processes(Tay, Panda et al. 2017). Due to the reason, level of adoption of 3D printing in the building & construction is very low(Wu, Zhao et al. 2018).With the integration of this technology with Building information modeling (BIM), planning, monitoring, safety and procurement at the construction sites can be managed well. Also, its application has the potential to open the window for the technology transfer and evolution of the interpersonal skills by the labor in order to meeting the needs of future(Tay, Panda et al. 2017). According to an experiment cum educational guess by the researchers, the cost of 3D printers is 0.5 to 0.75, cost of the materials is 0.2 to 0.4 times and labor charges are 0.05 to 0.30 times of the total production (Tofail, Koumoulos et al. 2018).Application of 3D Printing in the construction industry is limited and negligible. 3D Printing has the potential to disrupt the market, to bring new construction methods and techniques which in turn will change the designing and corresponding supply chain(Kothman and Faber 2016). The real business value of 3D Printing is still unknown due to lack of studies on the issue. Only a few people are aware of the application of this technology of 3D printing in the building and the construction industry, fewer of them can imagine the impacts of this technology on the construction projects(Panda, Tay et al. 2018). Conventional processes that are currently in business in construction industry are tiring and cumbersome having activities like formwork, skilled labor, work place injuries & illness, higher rate of fatalities. Research interests of the researchers are increasing day by day due to above mentioned issues of traditional construction process(Tay, Panda et al. 2017). Application of this technology in B&C industry is increasing slowly and gradually. International Advanced Architecture Catalonia (IAAC) designed and constructed a bridge with their own invention Mini builders. Mini builders are moveable, remote and automatic robotic 3D Printers that can help printing of building much larger than their size(Anjum, Dongre et al. 2017). Also, MX3D has printed a bridge in midair with metals without using any support structures. Also, different research-based companies are trying to optimize the mixing of printing materials. A team of research experts is working under the supervision of Prof Lawrence Sass MIT on 3DP of affordable housings in order to provide low cost housing facilities keeping in mind the availability of local materials (Anjum, Dongre et al. 2017). In Huazhong University of sciences and technology, researchers have managed to develop a combination of 3D Scanner and 3D Printers that can help in reproduction of damaged portions of historical building using Cement – sand mortar (Anjum, Dongre et al. 2017). Winsun printed first multi-storied 3D Printed building of China in 2015having an area of 1100sqm for its five stories in the time of just 17 days (Siddika, Mamun et al. 2020).3D printing is being perceived as a tool that can be helpful in addressing the issues like construction safety of the labors, increased construction waste, decreased availability of labors & higher cost associated with formwork etc. In 2017, almost 9 billion dollars is the estimated revenue generated due to application of 3D printing worldwide (Panda, Tay et al. 2018). In order to understand and adopt 3D printing, it is necessary to know “How it Works?”

2.2 Modeling and Working Procedures

A 3D printer transforms the design from a CAD file to a 3D object which is later divided into several 2D plans that guide the 3D printer regarding the exact location of deposition of material (Attaran 2017). With the advancement in computer software and hardware, making 3D computer graphics without much difficulties using various commercial and open source software, has become very easy. A model can be built in any commercially available software and then can be exported to STL (Stereolithography) format, which is the most common 3D exchange format in in the industry of 3D printing. This exported data is then divided into slices forming 2D contour lines knows as common layer interface (CLI) to develop control commands. These control commands control the position of laser beams and printer heads. The printer reads the CLI and control commands to 3D print and object. Complete process is shown in the Figure 2.1

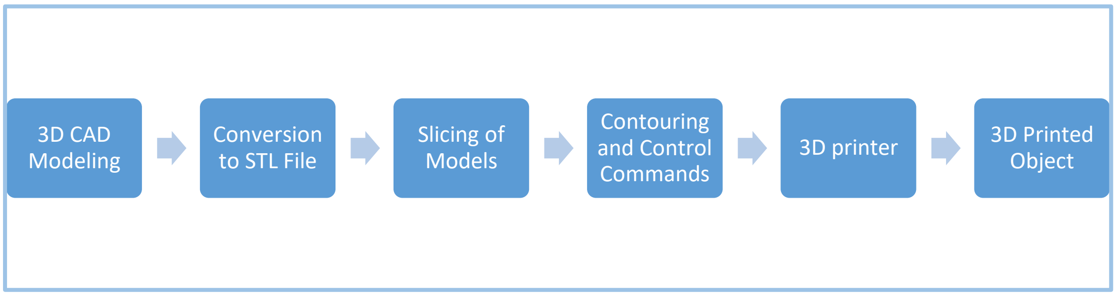


Figure 2.1 3D Printing Process(Raval and Patel 2020)

Additive manufacturing (AM) is a technique that utilizes layers to develop 3D objects from CAD files or digital models and allows users to make their own customize designs (Ashraf, Gibson et al. 2018). AM relies on the inter-dependency of multi parameters of the main components of construction, with each component having its own range of variable and parameters. Three main interrelated parameters need to be considered for a successful functioning of AM.

1. Printable feedstock: development of feedstock depends on mix design, composition, and source for optimized mixing, appropriate setting and open time, continuous supply to nozzle and smooth extrusion.
2. Printer: integration of printer with pump is necessary for the manufacturing scale, so the flow rate and pressure must be adjusted for different mix designs. The print quality depends on the size and speed of printer. The rate of deposition of feedstock effects the speed of construction and decreasing setting time may lead to setting of material inside the system of printer. Continuous feedstock delivery with optimized printing should ensure constant extrusion of material.
3. Geometry: design and effects of the above mentioned two parameters will influence building objects with self-reinforced and smart geometry. The stability of the shape of the extruded 3D curvatures and filaments ensures the stiffness and strength of printed building objects.

2.3 Current State of 3D Printing in Building and Construction Industry

Adoption of 3D printing in the construction industry is very slow and limited keeping in mind that this technology has been around for the last 30 years. However, the interest in 3D Printing has increased manifold over the last couple of years (Tay, Panda et al. 2017, Panda, Tay et al. 2018). Number of research papers published over the last couple of years has doubled the number of papers published over previous two decades, which shows the growing interest of the researchers in the area (Tay, Panda et al. 2017). As of now, 3D printing has come out of the issues related to patent rights & also growing research interest and sophistication has helped in increasing the rate of adoption of this technology in B&C industry (Panda, Tay et al. 2018). Initially different techniques were published in mid-90’s, one was based on cement-sand deposition with steam curing of mix and the other one was contour crafting which is a material deposition technique & is controlled with gantry type printers (Teymouri 2017). Different types of 3D Printers and 3D printing techniques have evolved in this period and research is paving way towards invention of more efficient, accurate and precise construction printers. Details of the 3D Printing process, 3D Printers and 3D Printed Projects are given in details below:

2.4 Types of 3D Printing Process

It is necessary to understand and learn the 3D printing processes for the understanding of advantages and benefits of using the 3D printing in B&C Industry. According to ISO / ASTM standards following are the types of 3D printers (Camacho, Clayton et al. 2018).

2.4.1 Vat Polymerization

This process of 3D printing uses a laser for the selective curing of a light activated polymer which is usually in liquid state (Camacho, Clayton et al. 2018). Stereo-lithography apparatus (SLA) and Digital Light Processing (DLP) work on the same principles (Tofail, Koumoulos et al. 2018) as shown in Fig 2.2 below. SLA was developed by Hull in 1980. At that time, this technique had patent related issues but was later commercialized by 3D systems (Camacho, Clayton et al. 2018). Excellent accuracy, excellent surface finish and printing the large parts are the main advantages while the limitations of this technique include slow build process, poor mechanical properties of the materials and limitation to photo-polymers only (Tofail, Koumoulos et al. 2018). Objects of sized 2100 mm x 700 mm x 800 mm or less can be printed by using vat polymerization (Tofail, Koumoulos et al. 2018).

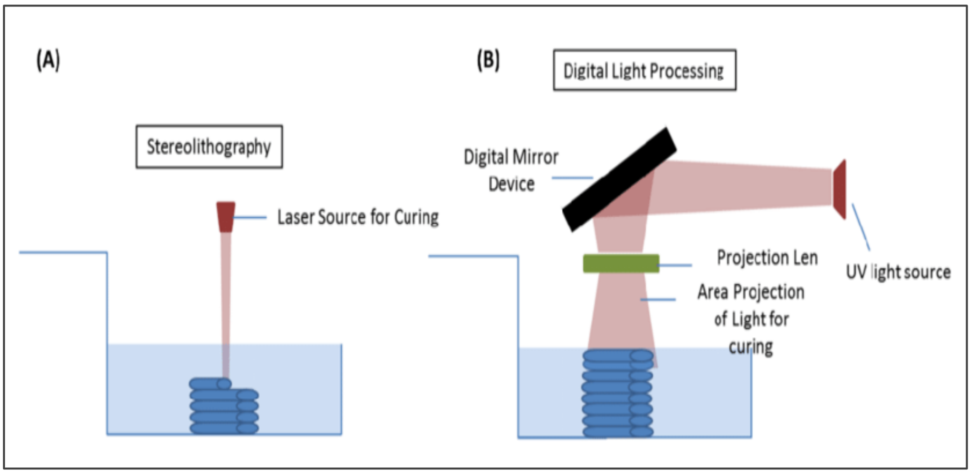


Figure 2.2 Stereo-lithography and Digital Light Processing following principle of Vat Polymerization(Tofail, Koumoulos et al. 2018)

2.4.2 Material Jetting

In this process of 3D Printings, material is selectively deposited drop by drop in layers or droplets of the materials are directly deposited for building purpose (Tofail, Koumoulos et al. 2018) as shown in Fig 2.3 below. Poly-jet technology by Stratasys, direct ink writing & 3D Inkjet technology are some of the examples of this process (Camacho, Clayton et al. 2018). High accuracy of material deposition, waste reduction & production of multicolor multi-material parts are main advantages of material jetting while requirement of support materials and viable material options are the main limitations of this process (Tofail, Koumoulos et al. 2018). Maximum printable size is 300mm x 200mm x 200mm and the infill materials usually used are polymers, composites (like concrete, cement-sand mortar etc.), Ceramics and biological (Tofail, Koumoulos et al. 2018).

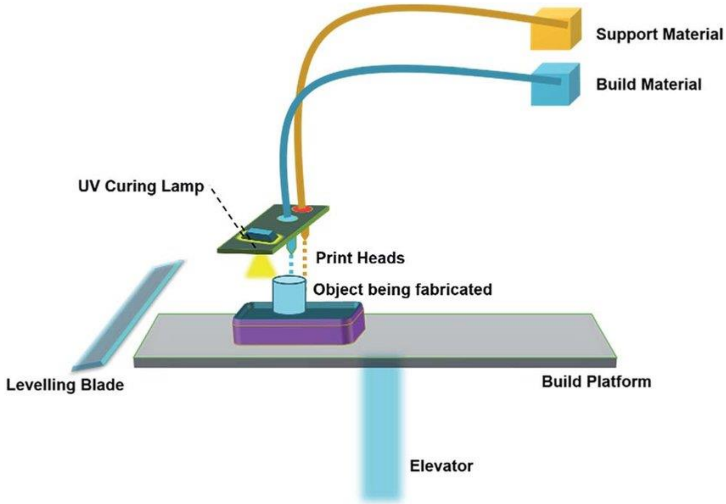


Figure 2.3 Schematic representation of material jetting(Camacho, Clayton et al. 2018)

2.4.3 Binder Jetting

In binder jetting, powdered material is deposited in a layer-wise fashion and a binder or binding materials are dropped on every layer for binding the powdered materials together (Bos, Wolfs et al. 2016, Tofail, Koumoulos et al. 2018) as shown in Fig 2.4. This technique was developed by the MIT researchers in a process which is called 3d Printing (Camacho, Clayton et al. 2018). 3D Inkjet technology is based on binder jetting technique. Large build volumes, high printing speed, design volumes and relatively low cost are the main benefits while the main limitation of this technique are fragility of the printed objects and requirement of post processing etc. Maximum printable size of this type of printers is 4000mm x 2000mm x 1000mm and materials that can be used are polymers, ceramics, composites, metals and hybrids (Tofail, Koumoulos et al. 2018).

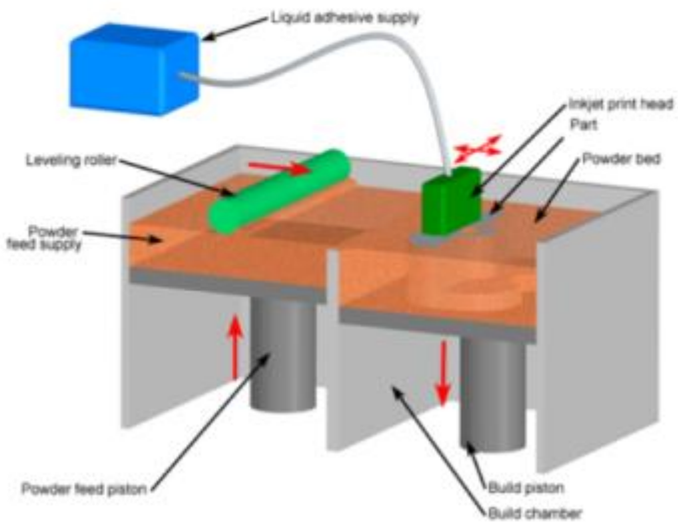


Figure 2.4 Binder Jetting at Loughborough University(Tofail, Koumoulos et al. 2018)

2.4.4 Material Extrusion

Material extrusion method or fused deposition modeling (FDM) is a technique which paved way towards invention and adoption of modern-day 3D Printers. FDM includes extrusion of materials through a nozzle or an orifice and it's deposited in layers on to a substrate (Tofail, Koumoulos et al. 2018). This process was developed by Crump and was later on commercialized by Stratasys (Camacho, Clayton et al. 2018). The schematic diagram of FDM is shown in the Fig 2.5 below. Fused Deposition Mode ling (FDM)/Fused Filament Fabrication (FFF) and Fused Layer Modeling (FLM) use the material extrusion principles for the purpose of 3D Printing. Wide spread use, inexpensiveness, customization and scalability are the main advantages of material extrusion techniques while the limitation include anisotropy in the vertical direction, layered finish quality and the more-fine details. The maximum printable size is 900mm x 600mm x 900mm and the infill materials used in the process of the printing includes polymers and composites (Tofail, Koumoulos et al. 2018).

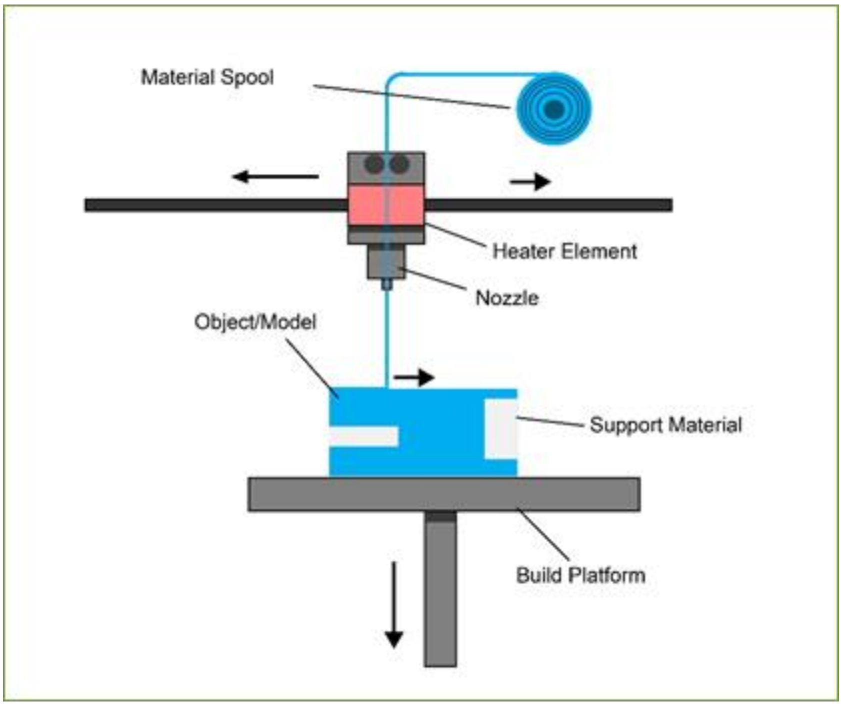


Figure 2.5 Schematic representation of material extrusion(Camacho, Clayton et al. 2018)

2.4.5 Powder Bed Fusion

In this process, thermal energy from electron beam or a laser is used for the fusion of a smaller region of a powder bed (Tofail, Koumoulos et al. 2018). The systematic diagram for this process is shown in Fig 2.6 below. Selective Laser Sintering (SLS) was developed for polymer-based printing materials by researchers at University of Texas. For fabrication and printing of metallic parts, Electronic Beam Melting (EBM), Selective Laser Melting (SLM), and Direct Metal Laser Sintering (DMLS) were developed as 3D printing techniques(Camacho, Clayton et al. 2018) Small foot print, relative inexpensiveness and large range of material options are the most important advantages of powder bed fusion technique and the disadvantages include lack of structural integrity, requirement of high power, slow processing and time consumptions, limitation of size and rough surface finish etc. Maximum printable size is 300mm x 300mm x 350mm and the infill materials include metals, ceramics, hybrids, composites and polymers (Tofail, Koumoulos et al. 2018).

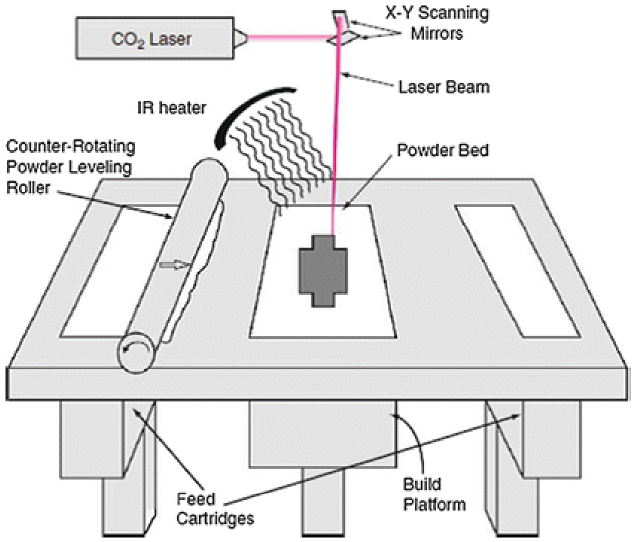


Figure 2.6 Powder bed fusion(Camacho, Clayton et al. 2018)

2.4.6 Sheet Lamination

In sheet lamination process of 3D Printing, objects are formed by continuously shaping and bonding sheets of materials(Camacho, Clayton et al. 2018). Laminated Object Manufacturing (LOM) and Ultrasound Additive Manufacturing (UAM) are sheet lamination techniques (Tofail, Koumoulos et al. 2018). Former technique involves sizing and gluing of paper sheets after proper trimming of the sheet to the required dimensions while the later uses ultra-sonic welding for fabrication of the metal objects. High speed, low cost and ease of handling materials are the major advantages of sheet lamination while strength of printed objects, finishes and limited material use are the main disadvantages of the sheet lamination technique. The sheet used in lamination process are shown in Fig 2.7 below.Maximum printable size of the objects is 250mm x 200mm x 150mm and the materials used for this technique are polymers, ceramics, metals & hybrids (Tofail, Koumoulos et al. 2018).

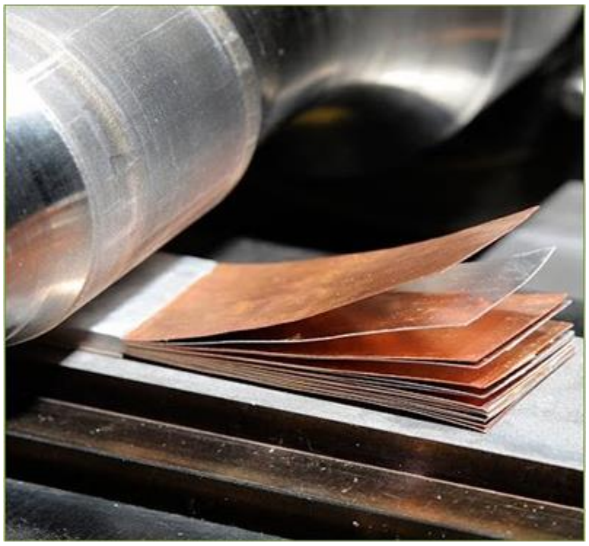


Figure 2. 7 Sheet Lamination(Tofail, Koumoulos et al. 2018)

2.4.7 Direct Energy Deposition

This process of 3D Printing melts down the material, at the time they are being deposited, with the help of focused thermal energy. Basically, this process uses fusion of materials as a tool for printing 3D objects. Sandia National Laboratories explored and developed the Laser Engineered Net Shaping (LENS) on the basis of direct energy deposition principles for repairing the damaged metal parts (Camacho, Clayton et al. 2018, Elasad and Amirov 2020). Other Direct Energy Deposition technologies include Laser Deposition (LD), Electron beam (EB) and Plasma arc melting. Widespread use, high quality finishing and rapid repairing of broken parts are the major advantages of the DED while disadvantages include imbalance between speed & surface quality and limited range of materials (Weinstein and Nawara 2015, Wu, Wang et al. 2016, Tofail, Koumoulos et al. 2018). Maximum printable size is 3000mm x 3500mm x 5000mm and the materials for which this technique can be used are metals and hybrids of metals only (Ma, Wang et al. 2018, Tofail, Koumoulos et al. 2018).

Table 2.1 Comparison of 3D Printing Processes

Category	Principle	Technology	Advantages	Disadvantages	Materials	Volume
Vat Polymerization	Liquid polymer is cured by light in a vat	Stereo Lithography (SLA)	Accuracy. Excellent surface finish. Greater details. Large parts.	Expensive and slow. Limited to only photopolymers. Poor mechanical properties and low shelf life,	Polymers Ceramics	Medium
Material Jetting	Build material is deposited in the form of droplets	3D Inkjet Technology	Low Waste. Multicolor. Accuracy of droplet deposition.Multiple material parts.	Use of polymers and thermoset resins mostly. Need of support material.	Polymers Ceramics Composites Hybrid Biological	Small
Binder Jetting	Liquid binder jets are printed on layers & are glued together to build the part	3D Inkjet Technology	Design Freedom. High printing speed. Low cost.Build volume large.Support free.	Post processing. Fragile parts.	Polymers Ceramics Composites Hybrid, Metals	Versatile
Material Extrusion	Material is extruded through an orifice or nozzle	Fused Deposition Modeling (FDM)	Inexpensive. Fully functional parts can be built.Scalable.Widespread use.	Fine details are not amenable. Step structure surface. Vertical anisotropy.	Polymers Composites	Small to medium
Powder Bed Fusion	A region of powder bed of build material is fused by thermal energy	Electron Beam Modeling (EBM)	Small footprint. Large material range. Inexpensive. Use of power bed as integrated support.	Size limitations. Finishing depends on powder size.Relatively slow.High power required. No structural integrity.	Metals Ceramics Polymers Composites Hybrids	Small
Sheet Lamination	Sheets of material are bonded	Laminated Object Manufacturing (LOM)	Low cost. High Speed. Ease of handling.	Limited material use. Strength depends on the used adhesive.	Polymers, Metals Ceramics, Hybrids	Small
Direct Energy Deposition	Materials are melted by focused thermal energy during deposition	Laser Deposition (LD)	Excellent repair application.High quality parts.Greater degree of	Requires balance between speed and surface quality. Limited to metallic hybrids.	Metals Hybrids	Versatile

			control of grain structure.			

Comparative advantages, disadvantages, technologies and processes used in 3D Printing are discussed in table 2.1 above. It is noticeable that there is no classic and standard classification of 3D Printing processes except for the one described above. Literature shows that definitions & classification of the 3D Printing processes changes based on the manufacturer, country, materials used and the target industry. Historically different organizations classified 3D Printing processes according to their own scales and standards. For example, US military space production & precision engineering department classified the 3D printing based on the type of material deposition, extrusion & layer connection methods. According to this classification, the most used types of 3D printing processes are Stereo-lithography (SL), Poly-jet Technology, MIT layer gluing technology & 3D Ink-jet Printers etc. These technologies use high energy lasers for selective curing of photo-reactive resins, spraying the photo-polymers followed by curing of every layer, gluing of layers of powdered materials and deposition the liquid binder over powder beds, respectively. The department declassified this categorization at the end of the patent period (Mukhamadeyeva 2020). A number of additive manufacturing technologies have been developed over the last couple of decades. However, the main and basic technologies which provided the base for the development of modern technologies can be identified(Ma and Wang 2018). All of the above-mentioned processes include creation of 3D Digital Models, slicing it into layers and real time printing of the sliced model by adding materials in layers. 3D Printing in the construction industry has also evolved and a number of 3D Printing technologies have been invented recently. Here is an introduction to the state-of-the-art 3D printing technologies in construction industry.

2.5 State of the art 3DPrinting Technologies in Construction

State of the art 3D printing technologies used in the building and the construction industry are divided, in most of the literature, into two main categories namely Binder Jetting (BJ) and Material Deposition Method (MDM) (Tay, Panda et al. 2017, Soltan and Li 2018). All other innovative 3D printing technologies use BJ & MDM as their core fabrication process. Basic principle of both the methods is real time printing of the 3D Models by the deposition of small quantities of material in a layer-wise manner. In order to avoid any deformation, the extruded materials should be having sufficient strength to sustain its own self-weight and also the weight of layers. MDM is similar to fused deposition modeling technique as a working process. MDM is the more discussed in the literature with respect to adoption of 3D printing in the construction as compared to BJ. According to researchers only 10% of the researchers discussed binder jetting as a 3D printing tool for construction purpose(Weinstein and Nawara 2015, Tay, Panda et al. 2017). Among all the developed 3D printing construction technologies only three printing technologies, namely Concrete Printing, D-Shape Printers and Contour crafting, have succeeded to grab the attention of the industry stakeholders and researchers (Teymouri 2017). Here are the introductory notes to the 3D printing technologies being used in the construction industry of the developed countries.

2.5.1 D Shape Printers

D-Shape printers, first invented by Enrico Dini as shown in Fig 2.8, are designed on the basic principles of binder jetting technique of 3D Printing. In D-shape printing, gantry-based powder bed printers are used for the purpose of printing and binder is sprayed over the layers of sand (Sakin and Kiroglu 2017, Teymouri 2017, Ghaffar, Corker et al. 2018). A thin layer of sand is laid & compacted up to the required thickness and then a magnesium-based binder is selectively deposited as per requirement of 3D Model with the help of nozzles mounted on the gantry. Sand and the binder react with each other & form a thin layer of solid stone and a sand-stone building is formed by layer-wise printing (Perkins and Skitmore 2015, Thiyagarajan 2017). Unbound sand acts as supporting material or formwork and paves way towards free-form construction. Production of waste decreases manifold with this method of 3D printing as the leftover sand can be removed with the help of vacuum cleaner after successful printing of the building & can be re-used after recycling. Use of finer materials like sand provides a good control over surface finish of print. Large scale components and sand-stone buildings can be printed & constructed with the help of D-shape printers (Ghaffar, Corker et al. 2018, Elasad and Amirov 2020). However, the sticky binder sticks to anything it touches including the nozzles & the printer itself which is a major limitation of Dini's D-shape printer.

Figure 2.8 D Shape Printers(Tay, Panda et al. 2017)

2.5.2 Contour Crafting(CC)

Contour crafting utilizes a gantry-based system that uses nozzles & robotic arms and follows the basic principle of Material Deposition Modeling which is layer-wise deposition of the materials according to layered 3D Digital Model. The additional & key feature of this technique is trowels attached with the nozzle of the printer which help in achieving more accurate & quality surface finish by guiding the materials in right directions as shown in Fig 2.9 below. The trowels are computer-controlled tools which can be deflected at different angles to print complex structures & shapes (Khoshnevis 2004). Thickness of the layer can be increased without affecting the surface finish which is mainly controlled by trowels. Structures are crafted from concrete & ceramic materials. There is provision for reinforcing and laying the conduits in the walls of contour crafted structures (Khoshnevis 2004, Tay, Panda et al. 2017)

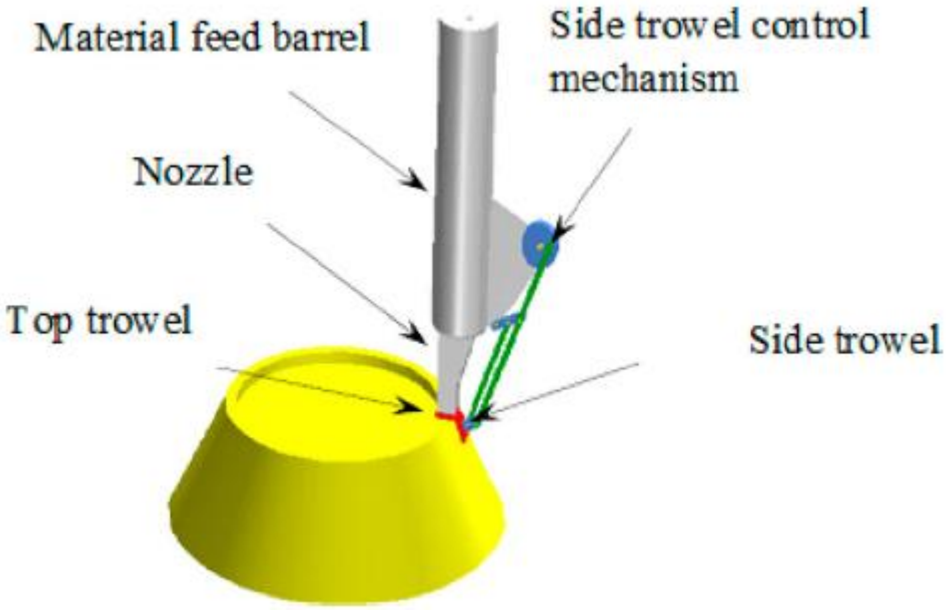


Figure 2. 9 Contour Crafting Process(Khoshnevis 2004)

2.5.3 Concrete Printing

Concrete printing is similar to CC and is built at Loughborough University, UK (Kidwell 2017, Ma and Wang 2018, Soltan and Li 2018). The technology has been in the development phase since 2004. The fabrication of first machine initiated in 2006 and was named as Freeform Construction machine. Concrete printing follows a digital model to extrude concrete lifts or layers through extrusion nozzles.The facility at Eindhoven University of Technology, 3DCP has adopted the approach of CC to develop a concrete printer (Hager, Golonka et al. 2016, Izard, Dubor et al. 2017)as shown in Fig 2.10. Water is added to the concrete and the mixture is pumped into a hose which is connected to the head of the printer. The printer head is located at the end of a motion-controlled vertical arm of a gantry robot having a four degree of freedom. The head prints a portion of concrete through a nozzle provided at is end, at a desired location, following a desired angle and speed.

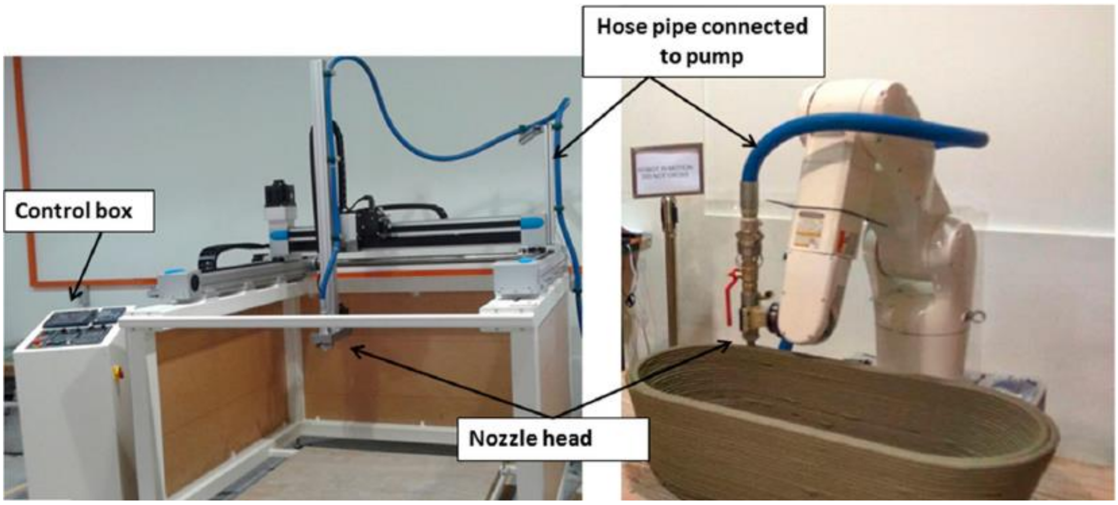


Figure 2.10 SC3DP Concrete Printer(Tay, Panda et al. 2017)

Specific terms describe the deposition of material which depends on the properties of fresh concrete. Over-printing is used to describe the condition when the material deposited is too much and that leads to bulging at specific points. Under-printing describes the condition when the deposited material is less than adequate. Under-printing may lead to breakage during the printing process. To cater for these conditions machine-operating parameters should be tuned appropriately and the tool path should be modified. Most of the concrete printers are flat layered printers and their two-dimensional deposition of material in flat layers sometimes lead to weaknesses in mechanical properties of concrete. (Bos, Wolfs et al. 2016), developed a concrete printer that follows the curved-layer method of printing that has improved the aesthetic aspects and mechanical properties of the deposited material. Current work in the scope of improvement in the concrete printers is predominantly focused on robotics development for placement of material, techniques of reinforcement, and the material science (Wu, Wang et al. 2016).

The similarities and differences between the D-shape, CC and concrete printing in the construction are summarized below in Table 2.2:

Table 2.2 Comparison of 3D Printers used for construction

	Contour Crafting	**D-Shape**	**Concrete Printing**
Process	Extrusion based	Selective binding	Extrusion based
Support	Vertical: no Horizontal: lintel	Unused powder	A second material
Material	Cementations material	Sand	High performance concrete
Printing Resolution	Low (15mm)	High (0.15 mm)	Low (9-20 mm)
Layer Thickness	13 mm	4-6 mm	5-25 mm
Print Head	1 nozzle	Hundreds of nozzles	1 nozzle
Nozzle Diameter	15 mm	0.15 mm	9-20 mm
Printing Speed	Fast	Slow	Slow
Printing Dimension	Mega-scale	Limited by Frame (6m x 6m x 6m)	Limited by frame

2.5.4 Stick Dispenser

Stick dispenser is a hand-held printer that is specially designed to enable a continuous feed of material composites in the form of chopsticks. These composites of chopstick material are developed by (Hager, Golonka et al. 2016)as shown in figure 2.11. The printing process comprises of randomly dropping wood glue coated chopsticks and forming a porous aggregated structure. This structure can later be evaluated by a volumetric analysis. A depth camera accompanied by a projector is used to guide the stick dispenser. Both the depth camera and projector help in identifying the location of deposited chopsticks by rendering color codes. The printing by this method requires low light conditions for the projector to operate. Various load tests are utilized to obtain the mechanical properties of the material printed. It has been proven in the recent past that structures printed by using this process have generally very low to absolutely no load-bearing capacities. Such structures are only utilized for aesthetic and innovative purposes during the construction of complex architectural features.

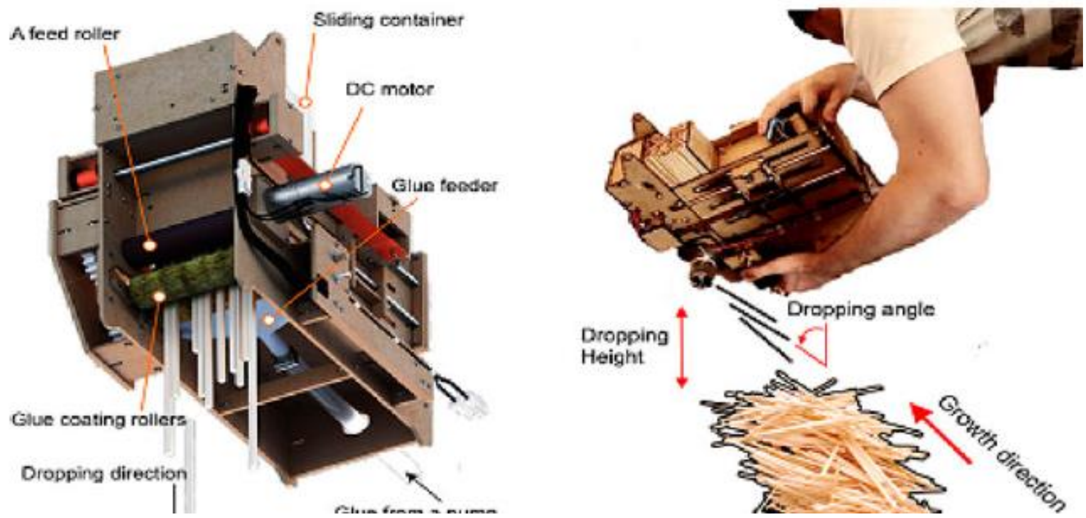


Figure 2.11 Stick Dispenser(Tay, Panda et al. 2017)

2.5.5 Digital Construction Platform

Digital construction platform is developed by researchers at the Massachusetts Institute of Technology (MIT) and is a system to be used for activities to be performed on site like sensing, fabrication and analysis (Alzarrad and Elhouar 2019). The system consists of a large boom the purpose of which is gross positioning to enhance and increase the accuracy, speed and access with the provision of a small robotic arm. It is a closed-loop system that can precisely position the effector by utilizing the accelerometer and ground reference sensors. The system utilizes polyurethane foam as the printing material as it has a high insulation value and a swift cure period. As a result of the same, the system would take hardly five minutes to print a twelve feet long wall. The end effector is also interchangeable which makes it very useful to obtain a fine surface end resolution by switching the end effector with a mill head.

2.5.6 Flow Based Fabrication

Flow based fabrication is a system that utilizes a pneumatic extrusion to extrude natural composites and polysaccharide gels (water based). The system was developed at the Massachusetts Institute of Technology (MIT). The pneumatic extrusion system is connected with end effector of robotic arm which is of six axes as shown in the figure below 2.12. The structure of the printed segment is fabricated and designed in a two-dimensional (2-D) form. The manufacturing and design of anisotropic material and heterogeneous structures can lead to lower weight, high stiffness, higher wear and resistance (Bogue 2018). The system finds its application in different translucency, architectural facades, and shading structures having lightweight.

Figure 2.12 Flow based Fabricated Prints(Tay, Panda et al. 2017)

2.5.7 Mini Builders

Mini builders are in the form of a system of three robots which are mobile, compact, and lightweight. This coordinated system is utilized in fabrication of various in-situ construction components. Each individual robot is assigned a different task during the printing process (Ngo, Kashani et al. 2018).

The types of robots and their functions are as follows:

- Foundation robot: utilizes a sensor and track for movement, places the initial or base layer.
- Grip robot: attached to the structure and has four rollers, uses steering actuator for positioning, prints curved and horizontal components and uses heater to accelerate curing.
- Vacuum robot: strengthen the printed components by previous robots by printing additional layers, can move at any angle.

2.6 3D Printing Materials

Usually the material used in 3D printing nowadays can be powder-like, solid-like, viscous-like, or liquid-like. 3D printers using powder-like material involve transformation the powdered material to a solid state by either sintering or melting(Thiyagarajan 2017, Ma and Wang 2018, Pierre, Weger et al. 2018). Power Binding Printing, Laser Sintering, D-Shape, Selective Laser Sintering and Selective Laser Melting are the examples of the 3D printers that use power-based material. The 3D printers using solid-like materials involves printing the material in the form of solid layers which are then glued together utilizing various available technologies. The 3D printing based on viscous-like materials utilize a printing nozzle to extrude the viscous material which is then cured to solidify it. Inkjet processes, Contour Crafting, and Fused Deposition Modeling are some of the processes that are based on the use of viscous-like material. Stereo lithography is a process that uses liquid-like material to 3D print a material by transforming the liquid material to a solid state by using a light source for the curing purposes. ISO/ASTM 52900 classifies feedstock material for AM as ceramic, metallic, polymers, and composites. Most of the research work has been done in the field of concrete-type or cementitious materials being used as extrusion material (Camacho, Clayton et al. 2018).

2.6.1 Concrete-Type Materials

The research in the field of 3D printing has focused itself on the use of concrete-type material owing to their unique characteristic of fresh and harden state and the possible variety of their feedstock to be generated. A small amount of variation in the mix design will have significant impacts on the material properties of fresh state (Dong, Milentis et al. 2018, Ghaffar, Corker et al. 2018)For viscous-like or cementitious material used in 3D printing to be succeeded, there are some certain requirements that needs to be optimized and considered. There are four characteristics that need optimization and consideration as per Ghaffar, Corker et al. (2018) which are:

1. Pumpability: ease with which printing material passes through the system.
2. Printability: ease with which printing material is deposited.
3. Buildability: resistance to deformations and support of upper layers by deposited material.
4. Open time: time in which above mentioned properties remain within accepted limits.

The most critical properties are printability and buildability (Tay, Panda et al. 2017, Yeh and Chen 2018). Both these properties depend on the adhesion between printed layers that constitute the bond strength. The bond strength depends on the time period between layers. An open time should be selected that is short enough to allow enough adhesion between layers and long enough to ensure proper curing (Ashraf, Gibson et al. 2018, Ghaffar, Corker et al. 2018).

A traditional mixture of concrete consists of coarse aggregates in defined proportions would not have sufficient flow through the extrusion nozzles. To cater for the same, the concrete mix must constitute of fine materials in larger proportion but, still it could include coarse aggregate in a significant amount to reduce the expected shrinkage (Hager, Golonka et al. 2016, De Schutter, Lesage et al. 2018). Certain admixtures and additives are present that can be used in aiding the flow of material and stabilizing its shape. According to researchers the use of admixtures have been successful in increasing the mixture fluidity but, the water content should be reduced to account for their use(Weinstein and Nawara 2015, Zhang, Zhang et al. 2018).

The study by Zhang, Zhang et al. (2018)on characteristics of concrete-type 3D printed material found the orthotropic behavior of extruded material which is not related to failure mode but can be relevant to elastic modulus and compression strength. The study proved that all extrusion-based printing processes are more likely to build strong orthotropic components that will affect the capacity of loadbearing. Also, the printing direction influence the bearing capacity of the extruded structure, and the mechanical behavior of printed elements is highly unpredictable which makes the structural performance of 3D printed material to be not reliable (Tay, Panda et al. 2017). Admixtures like superplasticizers, fly ash, silica fumes, micro-fibers etc. can be added to achieve or enhance specific properties like self-compaction, increased workability, high cohesion, and ductility (Ghaffar, Corker et al. 2018). Other admixtures can be added to reduce the carbon emissions or CO_2 footprint and to modify the viscosity.

The research facility at SC3DP is focusing on developing new concrete like 3D printable material like lightweight mortar, geo-polymer mortar, and fiber-reinforced mortar by using dust of crushed rocks like basalt and recycled glass aggregates. The facility conducts extensive laboratory testing to determine slump deformation, hardening and setting behavior of printable material after mixing. These laboratory testing is useful for determining appropriate printer speed, suitable pump pressure, and maximum number of layers of extruded component before being actually printed (Izard, Dubor et al. 2017). The 3D printed material's mechanical behavior is directly related to contact area and time gap between layers, and the material's viscosity (Ngo, Kashani et al. 2018).

2.6.2 Polymer-Based Materials

Polymer-based materials have low cost and low density and enable storage in a controllable and deposited state, unlike the concrete-type feedstock, and can be considered as feedstock for AM in the construction industry (Alzarrad and Elhouar 2019). Polymer-based material can be used in light weight structures and in the field of arts and sculpture due to their light weight. Such kind of material finds its application in merely prototypes because the products extruded using such material have less or no strength and load bearing capacity due to voids in their printed parts (Hager, Golonka et al. 2016, Ghaffar, Corker et al. 2018). Polymeric materials like nylon, photosensitive resin, elastomer, wax, and Acrylonitrile Butadiene styrene (ABS) can be used to build components by utilizing Selective Laser Sintering (SLS), Stereolithography (SLA), 3D printing processes, and Fused Deposition Modeling (FDM). Nylon finds its application in SLS as it is the most extensively researched and used polymer for bonds and melts (Pierre, Weger et al. 2018). ABS is a very popular polymer to be used in the FDM processes. Elastomers, waxes, and starch polymers are used quite often in 3D printing.

2.6.3 Metallic Materials

A number of small-scale industrial products like complex sand molds, antenna backers, repair and modification of burner tip of gas turbines etc. have been constructed by AM using metallic materials (Camacho, Clayton et al. 2018, Ngo, Kashani et al. 2018). Printing time and cost may limit the use of metallic material as printable material in AM in large scale manufacturing. Such materials are not extensively researched and very less examples are found in the past where those were employed using Powdered Bed Fusion (Buchanan and Gardner 2019).

2.7 Latest Innovations

In the current world, new generation three dimensional printers, construction 3D printers and large-scale printers are utilizing state of the art latest technologies to print a structure. Flying robots have been developed to overcome the limitations posed due to the height. An example of such is the Swarm-based large-scale three-dimensional printing. Hunt, Mitzalis et al. (2014)explored the applicability of such printers that utilize aerial additive construction, using a quad copter and in the mid-flight, deposited polyurethane foam. The limitation of such aerial projects may include the availability of material, the stability of the flight, battery life, and most importantly the regulations and restrictions of a state or country. Some of the latest innovations in the mentioned field are as follows.

2.7.1 Cazza Construction Technologies

Cazza manufactures and provides one the best latest three-dimensional printing technologies in the scope of civil engineering which are cost effective, environment friendly, and reliable. The company is manufacturing their own hardware and the construction material and has been successful in making their own concrete like material that is made from eighty percent recycled material. Apart from the latest construction material, the company is also developing latest machines that would be able to set up electricity and plumping automatically (Teymouri 2017)

One of Cazza's product is a crane-like portable 3D printer which can extrude the printing material layer by layer into the walls. The users can use the company's software to draw lines at which they want to print the material at desired heights and can also make their own three-dimensional models. Cazza claim that their 3D printer can construct a hundred squared mater house in a time span of twenty-four hours (Bogue 2018) at the site instead of printing it in pieces and then delivering it to the site. The company also claims that utilizing their 3D printers and automated constructions, pollution, amount of waste, and the cost can be reduced significantly.

Figure 2.13Cazza X1 construction robot developed by Cazza(Teymouri 2017)

2.7.2 CyBe Team

CyBe Construction has built CyBe RC 3D printer which is a mobile 3D printer mounted on caterpillar tracks as shown in the figure below 2.16. This is the very first of its kind. Its mobility makes it convenient to print on site at a high speed and extended range. The printer makes it possible to print on site sewer pits, formworks, and high walls with lower costs and under shorter duration. With reduction to waste and CO_2 emissions, the printed product is ecofriendly and of enhanced quality (Zhang, Li et al. 2018). CyBe team by introducing a mobile 3D printer, has redefined the whole construction industry by offering new solutions. The company's product offers cheap and faster construction than the conventional methods.

Figure 2. 14 Mobile concrete printer developed by CyBe(Teymouri 2017)

2.7.3 DUS Architecture

DUS architects used bio-plastic, a sustainable material to 3D print a cabin and bathtub, and named it the Urban Cabin. The main purpose was to offer solutions disaster relief or temporary housing. After its use, the cabin can be demolished and the all material used in it can be reused. The cabin was a research to explore the options of sustainable and compact living solutions in the current day urban locations along with offering smart solutions for materials and insulation (Teymouri 2017). Earlier in 2016, DUS architects also 3D printed a sculptural façade for a building reserved for European Union meeting, using fused deposition modelling.

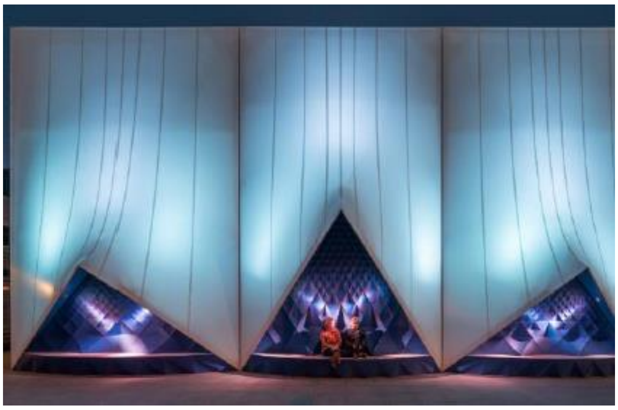


Figure 2.15 DUS Architecture Print Models(Teymouri 2017)

2.7.4 Free Fab Wax ™

Free Fab used two technologies, milling and 3D printing to deliver a shift in the production of molds used for Glass Reinforced Concrete (GRC) and precast concrete. The main advantage of utilizing two technologies is that the inherent limitations of one technology can be counted for by the strengths of the other technology. The main aim was to reduce the cost of fabrication of a mold to be used for a single panel. By doing do, Free Fab provided a smart, cost effective, and unique solution to construction sector dealing with structural elements used in buildings, within interiors, noise walls, and on bridges (Buchanan and Gardner 2019).

2.7.5 Bet-Abram ™

Bet-Abram has been manufacturing and selling a variety of 3D printers that have the ability to 3D print any model from a CAD file. Their 3D printer, Bet-Abram™ is a 3D concrete extrusion, gantry-based printer. Bet-Abram has 3 models, P1, P2, and P3, with P1 being the largest one. P1 can print products as large as sixteen meters, with two meters height, and nine meters width. Each model has a height limit of two meters which is a short coming and needs to be modified to print much larger objects (Furet, Poullain et al. 2019). The company claims that they use additives in the concrete mix to be used for their 3D printing.

Figure 2.16 Bet Abram TM 3D Printer(Teymouri 2017)

2.7.6 MX3DPrinters

MX3D’s printers can print sustainable materials in any dimension and shape as shown in fig 2.17. The company brought together robotics, digital technology, and traditional productions to develop a multi axis and economical 3D printer. The printer consists of a robot equipped with a latest welding machine that is software controlled. The printer could print midair resin, metals which are self-sufficient and don’t need support structures (Wilkinson 2018). The team 3D printed a steel bridge over OudezijdsAchterburgwal canal in Amsterdam which was the first of its kind and offered innovative solutions to manufacturing industry and transformed the arts industry (Teymouri 2017). The company kicked off the project in October 2015 when they opened their workshop. The support partners in this project were Arcelor, Heijmans, Autodesk, TU Delft, Lenovo, AMS, Mittal, ABB robotics, Air Liquide sponsors, Delcam, STV, and City Council of Amsterdam.

Figure 2.17 Final design of metal bridge by MX3D(Teymouri 2017)

2.7.7 Apis Cor

ApisCor 3D printer is a construction printer developed by ApisCor that can print permanent formwork for columns and strip foundations as well as walls and foundations that are self-supporting. The printer is relatively compact and has small dimensions that makes it easier to transport by a crane manipulator vehicle. The printer uses cement-based construction mix which has similar characteristics as that of concrete. The printer requires less time for setup and installation and ensure very less or no construction waste. The company recommends three stories of the printed building. The printer can take about two months to print a standard house including human errors and other risks(Camacho, Clayton et al. 2017). Because of its ability to print self-supporting structures, it can save up to seventy percent as compared to traditional methods on the building boxes used for erection. The company plans to develop functions of roof printing, placement of foundation placement, inter-story floors, and horizontal wall (Sakin and Kiroglu 2017).

2.7.8 Win-Sun ™

Also known by the name Ying-chuang, is a high-tech organization that develops latest material for construction. The company's main focus in on developing latest 3D construction printers and exploring new materials to be used in construction. The company has been using its 3D printing technology to assist in various urban construction sectors like, drainage and water supply, landscaping, sanitation, ancillary facilities, and underground utilities (Buchanan and Gardner 2019). The company also used its technology to 3D print the components required for a drainage facility located at Da Yang Mountain. The company plans to set up their units in UAE, Saudi Arabia, Morocco, Qatar, Tunisia, USA, and other more than twenty counties to popularize construction and building by 3D printing. Dubai office building printed by Winsun is shown in the fig 2.18 below. Their main aim is to target low-income families in Africa and Middle East to provide cheap as well as efficient housing (Teymouri 2017).

Figure 2.18 Dubai Office Building(Yin, Qu et al. 2018)

2.8 Structural and Architectural Aspects

3D printers have the ability to build more complex and innovative designs such as Fig 2.19. Shapes and designs that were almost impossible to construct by hand and were time consuming, are made possible with development of 3D printers (Zareiyan and Khoshnevis 2017). Printing objects has become easier and cheaper as compared to building them by the traditional methods. With the advancement of modeling software, digital architectural plans have become more common and digital graphics along with virtual images have made the architectural design more fascinating (Zareiyan and Khoshnevis 2017). Computer 3D models let viewers to see the designed structure from all angles before it is actually built. This makes it easier for the viewers to know more about their designs and improve the design reliability, visualization effects and integration.

Figure 2.19 3D Printed Architectural Structure(Teymouri 2017)

3D printers don’t differentiate between simple and complex structures, rather they print it(Wu, Zhao et al. 2018). 3D printers have proven to be a very valuable technology that can save our time as well as elevate the creativity. A lot of printing technologies are available that can be differentiated by the procedure they use to deposit and cure the material (Creegan and Anderson 2014). Laminated Object Manufacturing (LOM) have been merged with the 3D printers available nowadays, which are able to follow the roof’s double curvature as well as the load distribution, to better optimize the material consumption. The development of the design is an extensive iterative process that changes constantly depending upon the structural analysis (Wu, Wang et al. 2016, Wu, Zhao et al. 2018). The final shape and section of components of the roof are adapted to these changes. The very first step of this process defines the material to be used for the printing. Concrete because of its rheological and mechanical characteristics is usually identified as an ideal material (Asprone, Auricchio et al. 2018), and arched roof as the suitable solution to structural constraints. The elements are designed considering their weight and size so that they can be transported and handled on site easily.

2.9 Successful Projects

2.9.1 Radiolaria Pavilion(9 Sqm) – Italy (2009)

Shiro Studio collaborated with D-Shape to produce a free-form and complex 3 x 3 x 3 meters structure in Pontedera, Italy, in 2010. It is made of artificial sandstone without any internal reinforcement. It took 24 hours to complete the solidification process.

2.9.2 Netherlands Landscape House – Netherland (2013)

Universe Architecture in Amsterdam planned to 3D print a 6 x 9 meters fragments house using D-Shape printer. The sand type material was used to print the contours of building which were then strengthen with reinforced concrete. The project took 18 months to complete and final product is shown in Fig 2.20 below.

Figure 2.20 Netherlands Landscape House(Labonnote, Rønnquist et al. 2016)

2.9.3 Pedestrian Bridge – Nether Land (2016)

Researchers at Eidhoven University of Technology designed the first 3D 26 feet long and 3 feet thick printed concrete bridge at Gemert, Netherlands. The bridge was 3D printed using layers of concrete with steel cables and used less concrete. The bridge was 3D printed and installed in 7 days and shown in Fig 2.21 below.

Figure 2.21 Pedestrian Bridge – Netherlands(Labonnote, Rønnquist et al. 2016)

2.9.4 Ten Single Unit Houses - By Win-Sun In China (2014)

Win-Sun build 10 single story unit houses in Shanghai, China using their four 150 x 10 x 6.6 meters large 3D printers as shown in Fig 2.22. The material used was a mixture of construction waste and cement and each house was built for $5,000. Each house was 3D printed in a single day.

Figure 2.22Winsun Single Unit Houses – China(Kidwell 2017)

2.9.5 First 3d Printed House (298.5 Sqm) – Yaroslavi, Russia (2015)

AMT-SPECAVIA 3D printed a 298.5 square meters house using their S-6044 Construction 3D printer in Yaroslavi, Russia as shown in fig 2.23. They used a cement-based mixture as material know as M-300 sandcrete with a printing speed of 15 square meters per hour. The frame of the house was printed in a month.

Figure 2.23 First 3D Printed House – Russia(Ghaffar, Corker et al. 2018)

2.9.6 Building of Demand (Bod) - Europe (2018)

3D Printhuset printed a small office building in Copenhagen, Denmark using their 8 x 8 x 6 meters gantry type printer as shown in Fig 2.24 below. The printing speed was 2-5 meters/minute with each layer of 60 mm. The printing of walls took 50 hours and the total printing time exceeded two weeks. Recycled sand and tiles were used as concrete in printing material.

Figure 2.24 Building of Demand – Europe(Siddika, Mamun et al. 2020)

2.9.7 One Story Office Building (185 Sqm) – Dubai (2018)

Dubai and Winsun collaborated to 3D print a small office building using a 20 feet tall printer. The final finished building is shown previously in Fig 2.18. The building was printed layer by layer using reinforced concrete, plastic, glass fiber, and gypsum. The project cut the labor cost by 65% and construction time by 60%.

2.9.8 First 3D PrintedCommunity of 50 Houses – Mexico By Icon (2019)

ICON is 3D printing 500 feet squared apiece 500 houses in Tabasco, Mexico. Some of the houses already printed took 24 hours apiece and were printed by Vulcan 2 3D printer. The final finished unit is shown in Fig 2.25 below. The advantages of this project include affordability, high printing speed, resilience, continuum thermal envelope, zero waste, and high thermal mass.

Figure 2.25 ICON First 3D Printed Community(Siddika, Mamun et al. 2020)

2.9.10 Two Story Dubai Municipality Office (6.4sqm) – Dubai By Apis Cor (2019)

Apis Cor built the world’s largest 3D printed building in Dubai which is 9 meters high with floor area of 640 meter squared as shown in fig 2.26. Gypsum-based material was used as printing material for walls. Rebar was used in the reinforcement of 3D printed formwork.

Figure 2.26 Dubai Municipality Office by Apis Cor(Siddika, Mamun et al. 2020)

2.10 Opportunities & Benefits for Adoption of 3d Printing

The development of 3D printing has led to an increase in demand of manufacturing any part or product at different phases of supply chains (Tay, Panda et al. 2017). The 3D printers have revolutionized the supply chains because both the novices and experts can customize, design or even manufacture the products for their use locally. Thus, 3D printing has played an important role in transforming global supply chain to the local supply chain (Tay, Panda et al. 2017, Panda, Tay et al. 2018, Yeh and Chen 2018). This has led to the promotion of local products and transfer of energy. Therefore, large factories, malls, and ships could turn into mini factories, malls, and ships (Masera, Muscogiuri et al. 2017).

The AM has found its applications in various industries due to its advantages of building objects in considerably less duration of time with less consumption of material and human intervention. Using a 3D printer to build a structure would take approximately one quarter of the time that by using traditional methods would take for the equivalent structure (Ma, Wang et al. 2018). It has also improved our traditional strategies of building and reduced the need for large capital investment, human resources, and extra formworks (Tay, Panda et al. 2017).The formwork accounts up to forty percent of the budget for the concrete works, can be saved during the building, ultimately decreasing the project time span. There are no transport costs associated with 3D printed products as the designs can easily be transported digitally to the site and printed locally. 3D printers have reduced the possibility of injury at site by the elimination of dangerous jobs, increasing the safety level in the construction field (Yin, Qu et al. 2018). 3D printers operate at constant rate with high precision which can minimize the construction time and chances of error on site respectively. (Buswell, Soar et al. 2007) performed a cost benefit analysis and found out that the 3D printed products are suitable enough to compete for the customization and not for the mass production.

3D printing has the appropriate potential to build complex and innovative structures. The researchers are looking for the new material to be used as printable material which ultimately will increase the competition and will be scrutinized for low construction cost, and high quality (Tay, Panda et al. 2017). This will lead to bringing more value to the clients. 3D printed objects have high level of variation and details as 3D print designs can be customized and modified according to the user's desires and needs. The mentioned feature has provided architects with more freedom to be innovative in their designs. According to (Jiang, Zhao et al. 2016), creating unique and innovative products and adding details to facade will no longer be labor intensive and expensive due to 3D printers, with everyone given the opportunity to produce products in their local context. By taking advantage of the ability to deal with complex geometries, 3D printers have increased the multi functionality of architectural and structural elements (Ngo, Kashani et al. 2018).

The use of sustainable material has made 3D printing to be environment-friendly with less or no material wastage. Mega 3D printing industries can be setup to build 3D printed houses which are inexpensive especially in developing countries. Owing to the short construction time, 3D printed shelter homes can be built quickly to account for a tornado, earthquake, or any other natural disaster.3D Printing has the potential to reduce time for Construction by 50%-70%, labor costs by 40%-80% & construction waste by 30%-60% than conventional construction methods (Siddika, Mamun et al. 2020). NASA has already planned to build colonies on Mars using 3D printing technologies and companies like Wisun & Apis Cor etc has agreed to take up the challenge to print the building structures in Martian atmosphere (Alzarrad and Elhouar 2019). Here is a tabulated list of Identified Opportunities and benefits of 3D Printing in Construction Industry (Table 2.3):

Table 2.3 Identified Benefits through Literature Review

No	**Benefits**	**Reference**
1	Customized homes & building and Uniqueness in façade and other elements	(Khoshnevis 2004, Bos, Wolfs et al. 2016, Hager, Golonka et al. 2016, Labonnote, Rønnquist et al. 2016, Wu, Wang et al. 2016, Anjum, Dongre et al. 2017, Attaran 2017, Kidwell 2017, Tay, Panda et al. 2017, Teymouri 2017, Ashraf, Gibson et al. 2018, Camacho, Clayton et al. 2018, De Schutter, Lesage et al. 2018, Ngo, Kashani et al. 2018, Panda, Tay et al. 2018, Pierre, Weger et al. 2018, Tofail, Koumoulos et al. 2018, Wu, Zhao et al. 2018, Alzarrad and Elhouar 2019, Buchanan and Gardner 2019, Elasad and Amirov 2020, Siddika, Mamun et al. 2020)

2	Reduction of Construction Time	(Khoshnevis 2004, Bos, Wolfs et al. 2016, Hager, Golonka et al. 2016, Labonnote, Rønnquist et al. 2016, Wu, Wang et al. 2016, Anjum, Dongre et al. 2017, Attaran 2017, Kidwell 2017, Tay, Panda et al. 2017, Teymouri 2017, Ashraf, Gibson et al. 2018, Camacho, Clayton et al. 2018, De Schutter, Lesage et al. 2018, Ngo, Kashani et al. 2018, Panda, Tay et al. 2018, Pierre, Weger et al. 2018, Tofail, Koumoulos et al. 2018, Wu, Zhao et al. 2018, Alzarrad and Elhouar 2019, Buchanan and Gardner 2019, Elasad and Amirov 2020, Siddika, Mamun et al. 2020)
3	Reduced Material Waste	(Khoshnevis 2004, Perkins and Skitmore 2015, Labonnote, Rønnquist et al. 2016, Panda, Tay et al. 2016, Wu, Wang et al. 2016, Anjum, Dongre et al. 2017, Kazemian, Yuan et al. 2017, Tay, Panda et al. 2017, Ashraf, Gibson et al. 2018, Camacho, Clayton et al. 2018, De Schutter, Lesage et al. 2018, Ngo, Kashani et al. 2018, Pierre, Weger et al. 2018, Wu, Zhao et al. 2018, Yin, Qu et al. 2018, Alzarrad and Elhouar 2019, Buchanan and Gardner 2019, Elasad and Amirov 2020, Siddika, Mamun et al. 2020)

4	Saving in Construction cost	(Kothman and Faber 2016, Labonnote, Rønnquist et al. 2016, Wu, Wang et al. 2016, Anjum, Dongre et al. 2017, Attaran 2017, Khorramshahi and Mokhtari 2017, Kidwell 2017, Masera, Muscogiuri et al. 2017, Bogue 2018, De Schutter, Lesage et al. 2018, Ghaffar, Corker et al. 2018, Panda, Tay et al. 2018, Elasad and Amirov 2020, Siddika, Mamun et al. 2020)
5	Increased Sustainability	(Khoshnevis 2004, Hager, Golonka et al. 2016, Kothman and Faber 2016, Labonnote, Rønnquist et al. 2016, Attaran 2017, Khorramshahi and Mokhtari 2017, Kidwell 2017, Masera, Muscogiuri et al. 2017, Al Jassmi, Al Najjar et al. 2018, De Schutter, Lesage et al. 2018, Ghaffar, Corker et al. 2018, Tofail, Koumoulos et al. 2018, Alzarrad and Elhouar 2019, Buchanan and Gardner 2019, Siddika, Mamun et al. 2020)
6	Reduction of construction labor dependency & labor cost	(Khoshnevis 2004, Hager, Golonka et al. 2016, Kothman and Faber 2016, Labonnote, Rønnquist et al. 2016, Attaran 2017, Khorramshahi and Mokhtari 2017, Kidwell 2017, Masera, Muscogiuri et al. 2017, Al Jassmi, Al Najjar et al. 2018, De Schutter,

		Lesage et al. 2018, Ghaffar, Corker et al. 2018, Tofail, Koumoulos et al. 2018, Alzarrad and Elhouar 2019, Buchanan and Gardner 2019, Siddika, Mamun et al. 2020)
7	Flexibility to the Architects & Novel Shapes & Design	(Panda, 2018; Anjum, 2017; Ghaffar, 2018; Ghaffar, 2018; Attaran, 2017; Masera, 2017; Jassmi, 2018; Kothman and Faber, 2016; Wu, 2018; Kothman and Faber, 2016; Kidwell, 2017; Khorramshahi, 2017; Ngo, 2018; Labonnote, 2016; Labonnote, 2016; Tofail, 2017; Weinstein, 2015; Elasad et al, 2020; Babu et al 2019; Raval, 2020; Buchanan, 2019)
8	Environment Friendly Construction by using Recycled Material	Ghaffar, 2018; Attaran, 2017; Masera, 2017; Jassmi, 2018; Kothman and Faber, 2016; Kidwell, 2017; Khorramshahi, 2017; Subhedar, 2018; Ngo, 2018; Labonnote, 2016; Labonnote, 2016; Hager, 2016; De Schutter, 2018; Khoshnevis, 2004; Bogue, 2018; Siddika, 2019; Alzarrad, 2019; Babu et al 2019)
9	Improvement in productivity	(Panda, 2018; Ghaffar, 2018; Attaran, 2017; Wu, 2018; Ashraf, 2018; Ngo, 2018; Labonnote, 2016; Labonnote, 2016; De Schutter, 2018; GuoWei, 2017; Izard, 2017;

		Bogue, 2018; Elasad et al, 2020; Babu et al 2019; Babu et al 2019)
10	Safety in construction & remote area construction	(Anjum, 2017; Ghaffar, 2018; Kothman and Faber, 2016; Wu, 2018; Kothman and Faber, 2016; Khorramshahi, 2017; Bos, 2016; Hager, 2016; De Schutter, 2018; GuoWei, 2017; Khoshnevis, 2004; Bogue, 2018; Siddika, 2019; Raval, 2020; Buchanan, 2019)
11	In situ repair of construction areas with limited access	(Anjum, 2017; Ghaffar, 2018; Attaran, 2017; Kothman and Faber, 2016; Wu, 2018; Kothman and Faber, 2016; Khorramshahi, 2017; Bos, 2016; Ngo, 2018; Labonnote, 2016; Tofail, 2017; Izard, 2017; Khoshnevis, 2004; Buchanan, 2019)
12	Improved Quality	(Attaran, 2017; Wu, 2018; Panda, 2016; Subhedar, 2018; Ngo, 2018; Labonnote, 2016; De Schutter, 2018; Tofail, 2017; GuoWei, 2017; Siddika, 2019; Babu et al 2019; Alzarrad, 2019)
13	Printing the structure as a whole or in parts during disaster relief & rehab works	(Anjum, 2017; Attaran, 2017; Kothman and Faber, 2016; Kothman and Faber, 2016; Ashraf, 2018; Bos, 2016; Labonnote, 2016; Labonnote, 2016; De Schutter, 2018; Tofail, 2017; Raval, 2020; Buchanan, 2019)

14	Construction on other planets i.e. colonialization on Mars, Moon etc.	(Panda, 2018; Yei Wei Daniel Tay, 2017; Attaran, 2017; Ashraf, 2018; Khorramshahi, 2017; Labonnote, 2016; Yeh, 2018; GuoWei, 2017; Bogue, 2018; Siddika, 2019; Alzarrad, 2019)
15	Strength and durability of the 3D Printed Houses	(Ghaffar, 2018; Kothman and Faber, 2016; Kidwell, 2017; Ngo, 2018; Labonnote, 2016; De Schutter, 2018; GuoWei, 2017; Babu et al 2019)
16	Further incorporation of computer modelling e.g. 3D CAD, BIM (Rivet)	(Perkins and Skitmore, 2017; Kothman and Faber, 2016; Ngo, 2018; Labonnote, 2016; De Schutter, 2018; Bogue, 2018; Alzarrad, 2019; Buchanan, 2019)
17	Restoration, refurbishment & production of damaged parts of historical buildings	(Panda, 2018; Kothman and Faber, 2016; Ngo, 2018; Labonnote, 2016; De Schutter, 2018; Buchanan, 2019)
18	Automation in construction &Hybridization with conventional methods	(Anjum, 2017; Kothman and Faber, 2016; Kothman and Faber, 2016; Babu et al 2019; Alzarrad, 2019; Buchanan, 2019)
19	Ease of use	(Panda, 2018; Ghaffar, 2018; Kothman and Faber, 2016; Labonnote, 2016; Weinstein, 2015; Buchanan, 2019)

20	Reduction in expenses or cost variation due to lesser change orders	(Panda, 2018; Ghaffar, 2018; Attaran, 2017; De Schutter, 2018)
21	High end technology-based job creation	(Ghaffar, 2018; Khorramshahi, 2017; Weinstein, 2015; Alzarrad, 2019)
22	Visual representation	(Kothman and Faber, 2016; Labonnote, 2016; Siddika, 2019)
23	Better Work Flow Management	(Ghaffar, 2018; De Schutter, 2018; Buchanan, 2019)
24	Gain in Thermal insulation performance	(Jassmi, 2018)
25	Safer & Genderless Working conditions introducing a cultural Shift	(Ghaffar, 2018)

2.11 Challenges & Barriers to the Growth of 3D Printing

The printing of large building might not be possible as per many researchers due to the size requirements of 3D printers. The printing envelope of most of the 3D printers are relatively small and so the printed model would also be small. According to Teymouri (2017), 3D printing was mostly used to print parts of small sizes. One of the limitations of the 3D printing is the size of printer required to print the model (Alzarrad and Elhouar 2019). When the trend of 3D printing initiated, most the 3D printers were small scale and it is unclear whether these can be used to print large scale buildings as the size of 3D printers was related to the size of the building being printed. In the recent past, a number of large-scale buildings have been 3D printed using advanced and large 3D printers (Buswell, Soar et al. 2007). Another limitation is the stability and strength of the printing material used in printing that limit its use in large scale buildings (Alzarrad and Elhouar 2019). As per Khoshnevis (2004) the most commercially available and commonly used printing material is plaster that is light weight, cheap, and quick hardening but exhibits low wet strength and larger shrinkage. Clay has been found to be exhibiting sufficient wet strength but its stability has only been tested in small scale projects. The absence of high strength material to be used as printing material had limit the use of 3D printing technology in large scale buildings. Different materials have been modified to enhance their strength and stability properties in the recent past to be used as printing material to be extruded from the nozzles. The concrete to be used in printing should have buildability and extrudability characteristics to be properly extruded, have enough strength, stay in position, to support additional printed layers (Tofail, Koumoulos et al. 2018). The same can be attained by changing the mix proportions and by addition of admixtures that can achieve requisite compressive strengths (up to 107 MPa). It can be realistic to say that the same can be used in 3D printing large scale buildings as the concrete used in such projects have 60-100 MPa compressive strength. The current technological advancements in the 3D printing has made its use possible in large scale projects. The demand for customized products in construction industry is very less as compared to other industries and also the brittleness of the printable material needs to be improved (Anjum, Dongre et al. 2017, Panda, Tay et al. 2018). Some researchers argue that 3D printing would be expensive as compared to the conventional construction because of high up front digital modeling costs, cost of printers, and most importantly due to the fact that the current manpower is unfamiliar with this technology and its application in the construction industry (Attaran 2017, Khorramshahi and Mokhtari 2017). Here is a tabulated list of the challenges & barriers towards adoption of 3D printing in Building & Construction industry (Table 2.4):

Table 2.4 Identified Barriers through literature review

No	Factor	Reference
1	unavailability of suitable materials	(Panda, 2018; Yei Wei Daniel Tay, 2017; Anjum, 2017; Teymuri, 2017; Mukhamadeyeva, 2017; Perkins and Skitmore, 2017; Jassmi, 2018; Kothman and Faber, 2016; Wu, 2018; Panda, 2016; Camacho,2018; Kidwell, 2017; Bos, 2016; Subhedar, 2018; Ngo, 2018; Labonnote, 2016; Wu, 2016; Hager, 2016; De Schutter, 2018; Tofail, 2017; Weinstein, 2015; Yeh, 2018; GuoWei, 2017; Boshhenko, 2018; Elasad et al, 2020; Alzarrad, 2019; Raval, 2020; Buchanan, 2019)
2	High Costs of 3D Printers	(Anjum, 2017; Ghaffa, 2018; Teymuri, 2017; Attaran, 2017; Perkins and Skitmore, 2017; Masera, 2017; Kidwell, 2017; Ngo, 2018; Labonnote, 2016; Wu, 2016; De Schutter, 2018; Tofail, 2017; Weinstein, 2015; Yeh, 2018; GuoWei, 2017; Boshhenko, 2018; Siddika, 2019; Elasad et al, 2020; Alzarrad, 2019; Raval, 2020; Buchanan, 2019)
3	Lack of Codes, guidelines & Regulations	(Panda, 2018; Ghaffa, 2018; Teymuri, 2017; Mukhamadeyeva, 2017; Attaran, 2017; Perkins and Skitmore, 2017; Jassmi, 2018;

		Kothman and Faber, 2016; Wu, 2018; Camacho, 2018; Kidwell, 2017; Labonnote, 2016; Tofail, 2017; Weinstein, 2015; Yeh, 2018; GuoWei, 2017; Khoshnevis, 2004; Siddika, 2019; Elasad et al, 2020; Alzarrad, 2019; Buchanan, 2019)
4	Quality related issues like void formation & rough surface finish	(Panda, 2018; Ghaffa, 2018; Kothman and Faber, 2016; Wu, 2018; Panda, 2016; Camacho, 2018; Bos, 2016; Subhedar, 2018; Ngo, 2018; Labonnote, 2016; Wu, 2016; De Schutter, 2018; Tofail, 2017; GuoWei, 2017; Izard, 2017; Boshhenko, 2018; Siddika, 2019; Elasad et al, 2020; Buchanan, 2019)
5	Scale, size & weight etc of 3D Printers	(Anjum, 2017; Teymuri, 2017; Mukhamadeyeva, 2017; Attaran, 2017; Skitmore, 2017; Masera, 2017; Camacho, 2018; Ngo, 2018; Labonnote, 2016; Wu, 2016; Wu, 2016; Tofail, 2017; Weinstein, 2015; Yeh, 2018; GuoWei, 2017; Boshhenko, 2018; Alzarrad, 2019; Raval, 2020)
6	Non compatibility with raw materials	(Panda, 2018; Yei Wei Daniel Tay, 2017; Anjum, 2017; Skitmore, 2017; Camacho,2018; Kidwell, 2017; Bos, 2016; Subhedar, 2018; Ngo, 2018; Wu, 2016; Hager, 2016; De Schutter, 2018; Tofail, 2017;

		Weinstein, 2015; Boshhenko, 2018; Elasad et al, 2020)
7	Unsuitability of Conventional Design approach	(Panda, 2018; Anjum, 2017; Teymuri, 2017; Skitmore, 2017; Kothman and Faber, 2016; Ashraf, 2018; Kidwell, 2017; Ngo, 2018; Labonnote, 2016; Wu, 2016; De Schutter, 2018; Tofail, 2017; Raval, 2020; Buchanan, 2019)
8	Economics of scale (for small enterprises, printer size etc)	(Anjum, 2017; Skitmore, 2017; Subhedar, 2018; Ngo, 2018; Labonnote, 2016; Wu, 2016; De Schutter, 2018; Tofail, 2017; Weinstein, 2015; Yeh, 2018; Elasad et al, 2020; Alzarrad, 2019)
9	Precision of Printed part still needs improvement	(Ghaffar, 2018; Kothman and Faber, 2016; Panda, 2016; Subhedar, 2018; Ngo, 2018; Labonnote, 2016; Hager, 2016; De Schutter, 2018; Izard, 2017; Boshhenko, 2018; Siddika, 2019; Buchanan, 2019)
10	Lower Strength and testing procedures	(Panda, 2018; Yei Wei Daniel Tay, 2017; Anjum, 2017; Skitmore, 2017; Kothman and Faber, 2016; Camacho,2018; Ashraf, 2018; Bos, 2016; Ngo, 2018; De Schutter, 2018; Boshhenko, 2018; Alzarrad, 2019)

11	lower Sustainability of 3D Printed Structure due weak bond b/w layers	(Panda, 2018; Anjum, 2017; Kothman and Faber, 2016; Ashraf, 2018; Kidwell, 2017; Ngo, 2018; Wu, 2016; De Schutter, 2018; GuoWei, 2017; Siddika, 2019; Alzarrad, 2019)
12	Final Cost of the 3D Printed building is uncertain and difficult to Estimate	(Masera, 2017; Kothman and Faber, 2016; Wu, 2018; Camacho,2018; Ngo, 2018; Labonnote, 2016; Wu, 2016; De Schutter, 2018; Tofail, 2017; Buchanan, 2019)
13	Lack of Research and Knowledge	(Anjum, 2017; Teymuri, 2017; Panda, 2016; Camacho,2018; Kidwell, 2017; Boshhenko, 2018; Siddika, 2019; Elasad et al, 2020; Alzarrad, 2019; Buchanan, 2019)
14	Printing complex structures	(Anjum, 2017; Panda, 2016; Camacho,2018; Ashraf, 2018; Ngo, 2018; Labonnote, 2016; Wu, 2016; De Schutter, 2018; Tofail, 2017; GuoWei, 2017)
15	Low Printing Rate & Productivity	(Camacho, 2018; Ashraf, 2018; Ngo, 2018; Labonnote, 2016; Wu, 2016; De Schutter, 2018; Tofail, 2017; Raval, 2020; Buchanan, 2019)
16	Technology Readiness	(Wu, 2018; Ngo, 2018; Labonnote, 2016; Wu, 2016; Hager, 2016; De Schutter, 2018; Yeh, 2018; GuoWei, 2017)

17	Transportation of Equipment and Prefab 3D Printed Structures	(Masera, 2017; Kothman and Faber, 2016; Camacho, 2018; Ashraf, 2018; Weinstein, 2015; Khoshnevis, 2004; Boshhenko, 2018; Raval, 2020)
18	Resistance to changes and transformations & Lack of technical support	(Teymuri, 2017; Mukhamadeyeva, 2017; Wu, 2018; Khorramshahi, 2017; Ngo, 2018; Yeh, 2018; Raval, 2020; Buchanan, 2019)
19	Anisotropic properties of materials & Mechanical Properties	(Bos, 2016; Subhedar, 2018; Ngo, 2018; De Schutter, 2018; Boshhenko, 2018; Siddika, 2019; Buchanan, 2019)
20	Support Structures are required	(Subhedar, 2018; Ngo, 2018; Wu, 2016; De Schutter, 2018; Siddika, 2019; Buchanan, 2019)
21	Huge gap between Architectural Ideas and Manufacturing	(Teymuri, 2017; Kothman and Faber, 2016; Ngo, 2018; Labonnote, 2016; Tofail, 2017; Buchanan, 2019)
22	Requirement of 3D Digital Models	(Anjum, 2017; Panda, 2016; De Schutter, 2018; Alzarrad, 2019; Raval, 2020; Buchanan, 2019)
23	Organizational Support & Top management commitment	(Wu, 2018; Camacho, 2018; Khorramshahi, 2017; Yeh, 2018; GuoWei, 2017)

24	End user acceptability	(Anjum, 2017; Camacho, 2018; Khorramshahi, 2017; Weinstein, 2015; Buchanan, 2019)
25	Higher resolution requiring thinner layers and more time	(Camacho, 2018; Ngo, 2018; Izard, 2017; Boshhenko, 2018)
26	High level of abrasiveness of concrete requires maintenance	(Ghaffar, 2018; Ngo, 2018; Wu, 2016; Hager, 2016)
27	Material Change over is difficult	(Bos, 2016; Subhedar, 2018; Ngo, 2018; Wu, 2016)
28	Managerial Issues	(Teymuri, 2017; Skitmore, 2017; Wu, 2018; Yeh, 2018)
29	Negative social impacts like unemployment due to fully automated system	(Khorramshahi, 2017; Hager, 2016; Weinstein, 2015; Buchanan, 2019)
30	Technology Transfer	(Anjum, 2017; Teymuri, 2017; Panda, 2016; Labonnote, 2016)
31	Compatibility with work packages	(Anjum, 2017; Kidwell, 2017; Ngo, 2018; Wu, 2016)
32	Divergent from Design to Execution	(Ngo, 2018; Labonnote, 2016; De Schutter, 2018; Tofail, 2017)
33	Unsuitable Fabrication Technologies	(Teymuri, 2017; Skitmore, 2017; Hager, 2016)

34	Who will take the liability in case of failure	(Ngo, 2018; Labonnote, 2016; Buchanan, 2019)
35	Intellectual property and patent related issues	(Ngo, 2018; Labonnote, 2016)
36	Active control of rheology and stiffening	(Ngo, 2018; De Schutter, 2018)
37	Successful Cases	(Wu, 2018; Elasad et al, 2020)

Chapter 3

3. METHODOLOGY

3.1 Introduction

This chapter will explain the intended approach to achieve the objectives of this research as stated in Chapter 1. Techniques like literature review, expert interviews, surveys and statistical analysis will be used in this research.

3.2 Research Design

Research methodology refers to a logical stepwise process to carry out any research work. This study will be conducted through various distinctive phases which include literature review, identification of factors affecting the adoption of 3D Printing in construction, ranking the identified factors to find key parameters, development of a frame work for adoption of 3D Printing in construction industry of developing countries, results, discussions and recommendations as shown in Figure 3.1. The schematic diagram shows the research methodology which will be adopted for this research. It will include inputs from both literature and industry experts for the development of a roadmap towards adoption of 3D Printing in Construction Industry of Developing countries.

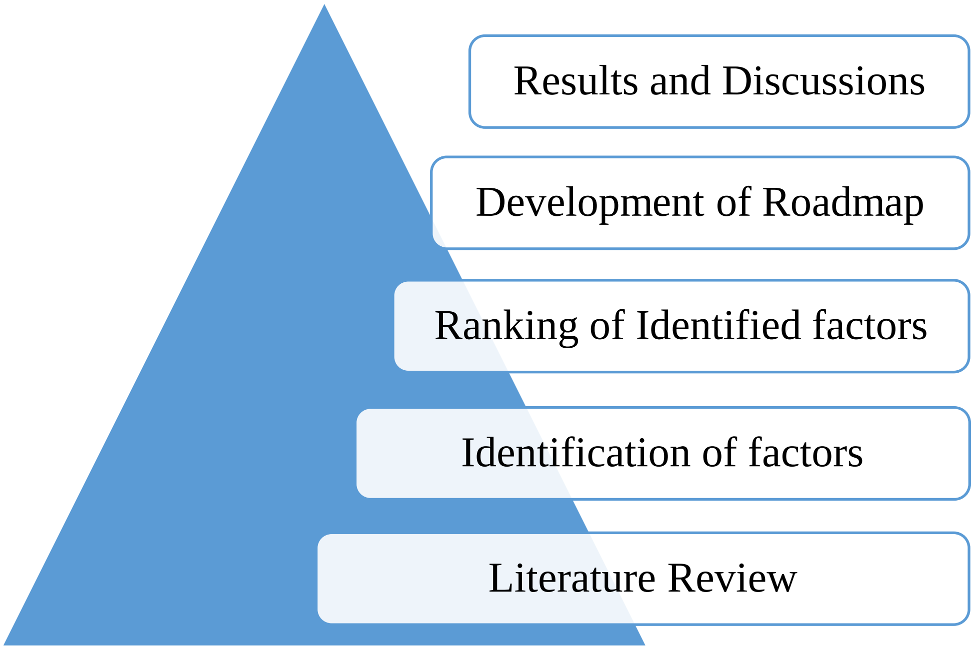


Figure 3. 1 Research Methodology Pyramid

3.2.1 Literature Review

This research began with identification of a research gap through preliminary literature review. Research publications for the adoption of a wider group of advance technologies in the construction industry of developed countries were studied and 3D Printing technology was identified as a total automation technology which is still in its infancy in construction industry. After identification of this research gap, published studies under the titles of application of 3D printing in construction, 3D Printing materials, 3D Printing technologies, challenges and barriers towards application of 3D printing in construction industry were studied and methodology for this research was established. The published literature was explored in the databases of Emerald, Taylor & Francis, Elsevier, ASCE & Google Scholar. The keywords used for the searching the literature include '3D Printing in Construction' 'Concrete Printing' 'Contour Crafting' 'Additive manufacturing in construction' 'Adoption of 3D Printing' 'Challenges &Barriers to 3D printing in Construction' '3D Printing Materials' 'Rapid Prototyping and Construction' etc. The studies found on the subject were further scrutinized and a total of 82 papers were found to be relevant to this study. These papers were further distributed into four categories such that 39 papers are for the adoption of 3D Printing in Construction, 19 are about 3D Printing materials for construction, 8 about 3D Printing Technologies and 16 are for miscellaneous category which includes different review and less relevant papers. A thorough content analysis was performed for 39 papers related to adoption of 3D Printing. As a result, a total of 25 benefits and opportunities while 37 Challenges and barriers towards adoption of 3D Printing in construction were found and listed for further analysis.

3.2.2 Identification & ranking of key Benefits and Barriers

In order to identify and rank the key factors for adoption of 3D Printing, the technique of systematic literature review was performed(Ullah, Ayub et al. 2016). The benefits and barriers were ranked on the basis of a combined score which includes both literature score (LS) and industry score (IS).LS score was calculated through a literature-based frequency analysis while IS was calculated based on the results of a structured online preliminary survey distributed among industry experts of developing countries. Questionnaire survey is attached in Annexure-I. The frequencies for appearance of each factors was carefully recorded in order to avoid duplication and organized to perform frequency analysis. Equation 3.1 was used for calculation of Literature Score (LS) for each factor where $f$is frequency of each factor, Σf is the cumulative frequency of all the factors.

$$LS = f / \Sigma(f) \qquad (3.1)$$

For calculation of industry score for the barriers and opportunities towards adoption of 3D printing, an online preliminary survey was conducted and respondents were asked to mark the impact of each factor on a Likert scale of 0 to 5, where 0 represents “no effect” & 5 represents “very high effect”. A total of 40 responses were collected out of which 30 most experienced & valid responses were selected for further analysis. Statistical tests were performed for reliability of data (Cronbach Alpha) and Analysis of variance (ANOVA).

To calculate final score (*FS*) of each factor, multiple combinations of different weightages (e.g. 50-50 ,60-40 & 80-20) for literature score (*LS*) and Industry Score (IS) were tested and analyzed. ANOVA test and null hypothesis proved that there was no significant difference and any of the assigned weightage can be used for ranking of identified factors. As most of the research was performed in developed countries, therefore industry score was given a little more weightage as compared to literature score and 60-40 combination was selected for ranking of key factors. The benefits and challenges were ranked on the basis of final score and combined significance for each factor was calculated i.e. cumulative normalized score. Key benefits and challenges were selected up to a combined significance of 60% for further analysis and provision of road map towards adoption of 3D Printing in Construction (Ullah, Thaheem et al. 2017).

3.2.3 Development of Roadmap

A comprehensive data collection in the form of interviews from local industry professionals and online survey from professionals of developing countries was conducted via type-set questionnaire as secondary data collection(Ahmad, Thaheem et al. 2018, Ahmed, Thaheem et al. 2019). Questionnaire for these interviews is attached as Annex-II. This questionnaire was divided into four parts and it contained open ended question for respondents. First part of the questionnaire was introduction to the study & second part contained questions regarding demographic information of the respondents. In third and fourth part, respondents were asked for recommendation regarding how can the effects of key barriers and opportunities towards adoption of 3D printing in Construction Industry be optimized. A total of 33 responses were received (15 from Interviews & 18 from Type-set questionnaire) and 30 were shortlisted for further analysis. Strategies and recommendations from responses were found, listed and their frequency was calculated for each factor. Frequency analysis was performed and recommendations were ranked on the basis of cumulative normalized score. Either top three recommendation or recommendation with a combined significance of at least 60% were shortlisted from each category for development of roadmap towards adoption of 3D Printing in building & construction industry of developing countries. Finally, recommendations and limitations of the study are discussed which will pave way towards future research in the area.

Chapter 4

4. RESULTS AND ANALYSIS

4.1 Introduction

Analysis performed on the collected data is covered in this chapter. It also covers the detailed results and discussions on the findings of the study.

4.2 Identification of benefits and barriers

A comprehensive literature review was carried out in the first phase of the properly structured methodology as discussed earlier in chapter 3. A total of 25 benefits and 37 barriers towards adoption of 3D Printing in construction industry were identified through thorough literature review. Frequency analysis was performed and identified factors and barriers were ranked on the basis of their frequencies of appearance in the literature. Literature score was calculated for each benefit and barrier. Two different analysis sheets for benefits and barriers were used in this study. Normalized score was calculated for each factor and factors were ranked according to cumulative normalized scores. Results of this statistical analysis for benefits and barriers are shown in the Table 4.1 & 4.2 respectively. Customization in design & façade of the buildings & reduction in construction time were identified as top two benefits with literature scores of 0.093 & 0.090 respectively.

Table 4.1 : Literature score values for benefits towards adoption of 3D Printing

Sr #	Benefits / Opportunities	Normalized Score / LS	Cumulative Score
1	Customized homes & building and Uniqueness in façade and other elements	0.09317	0.09317

2	Reduction of construction time	0.09006	0.18323
3	Reduced material waste	0.08385	0.26708
4	Saving in construction cost	0.07453	0.34161
5	Increased sustainability	0.07143	0.41304
6	Reduction of construction labor dependency & labor cost	0.06522	0.47826
7	Flexibility to the architects & novel shapes & design	0.06522	0.54348
8	Environment friendly construction by using recycled material	0.05590	0.59938
9	Improvement in productivity	0.04658	0.64596
10	Safety in construction & remote area construction	0.04658	0.69255
11	In situ repair of construction areas with limited access	0.04348	0.73602
12	Improved quality	0.03727	0.77329
13	Printing the structure as a whole or in parts during disaster relief & rehab works	0.03727	0.81056

14	Construction on other planets i.e. colonialization on Mars, Moon etc.	0.03416	0.84472
15	Strength and durability of the 3D printed houses	0.02484	0.86957
16	Further incorporation of computer modelling e.g. 3D CAD, BIM (Rivet)	0.02484	0.89441
17	Restoration, refurbishment & production of damaged parts of historical buildings	0.02174	0.91615
18	Automation in construction & hybridization with conventional methods	0.01863	0.93478
19	Ease of use	0.01553	0.95031
20	Reduction in expenses or cost variation due to lesser change orders	0.01242	0.96273
21	High end technology-based job creation	0.01242	0.97516
22	Visual representation	0.00932	0.98447
23	Better Workflow Management	0.00932	0.99379
24	Gain in thermal insulation performance	0.00311	0.99689
25	Safer & genderless working conditions introducing a cultural shift	0.00311	1.00000

Similar analysis was carried out for barriers towards adoption of 3D printing in construction industry & unavailability of suitable materials and high cost of 3D printers were identified as top two barriers with literature scores of 0.075 & 0.066 respectively as shown in Table 4.2 below.

Table 4.2 : Literature score values for challenges towards adoption of 3D Printing

Sr. #	Challenges / Barriers	Normalized Score / LS	Cumulative Score
1	Unavailability of suitable materials	0.07500	0.07500
2	High costs of 3D printers	0.06563	0.14063
3	Lack of Codes, guidelines & regulations	0.06563	0.20625
4	Quality related issues like void formation & rough surface finish	0.05938	0.26563
5	Scale, size & weight etc of 3D Printers	0.05313	0.31875
6	Non compatibility with raw materials	0.04688	0.36563
7	Unsuitability of conventional design approach	0.04375	0.40938
8	Economics of scale (for small enterprises, printer size etc.)	0.03750	0.44688

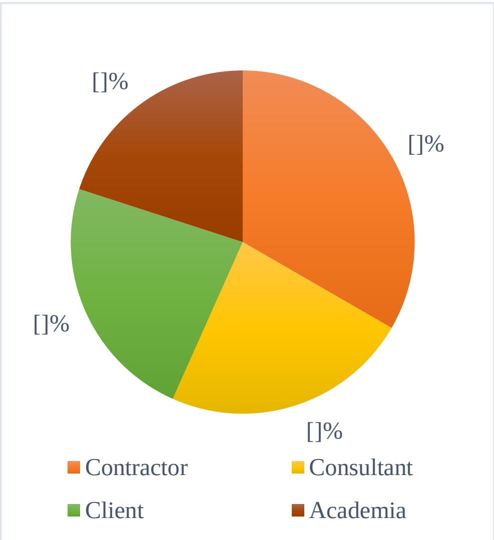
9	Precision of printed part still needs improvement	0.03750	0.48438
10	Lower strength and testing procedures	0.03750	0.52188
11	Lower sustainability of 3D printed structure due weak bond between layers	0.03438	0.55625
12	Final cost of the 3D printed building is uncertain and difficult to estimate	0.03125	0.58750
13	Lack of research and knowledge	0.03125	0.61875
14	Printing complex structures	0.03125	0.65000
15	Low printing rate & productivity	0.02813	0.67813
16	Technology readiness	0.02500	0.70313
17	Transportation of equipment and prefab 3D printed structures	0.02500	0.72813
18	Resistance to changes and transformations & Lack of technical support	0.02500	0.75313
19	Anisotropic properties of materials & mechanical properties	0.02188	0.77500
20	Support structures are required	0.01875	0.79375

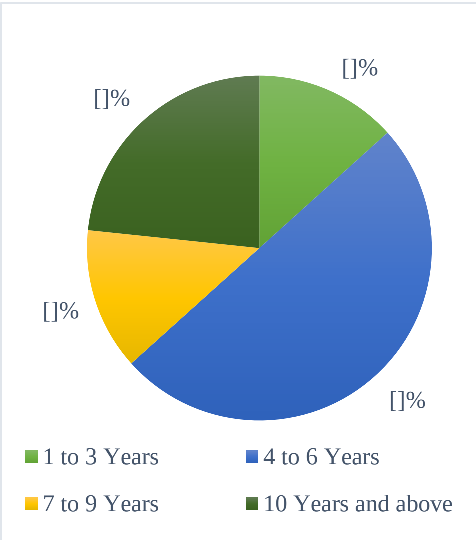
21	Huge gap between architectural ideas and manufacturing / printing	0.01875	0.81250
22	Requirement of 3D Digital Models	0.01875	0.83125
23	Organizational support & top management commitment	0.01563	0.84688
24	End user acceptability	0.01563	0.86250
25	Higher resolution requiring thinner layers and more time	0.01250	0.87500
26	High level of abrasiveness of concrete requires maintenance	0.01250	0.88750
27	Material change over is difficult	0.01250	0.90000
28	Managerial issues	0.01250	0.91250
29	Negative social impacts like unemployment due to fully automated system	0.01250	0.92500
30	Technology transfer	0.01250	0.93750
31	Compatibility with work packages	0.01250	0.95000
32	Divergent from Design to Execution	0.01250	0.96250

33	Unsuitable fabrication technologies	0.00938	0.97188
34	who will take the liability in case of failure	0.00938	0.98125
35	Intellectual property and patent related issues	0.00625	0.98750
36	Active control of rheology and stiffening	0.00625	0.99375
37	Lack of successful cases	0.00625	1.00000

4.3 Preliminary Survey

A detailed survey was conducted in the second phase of the study, in order to incorporate feedback from industry professionals regarding 25 benefits and 37 barriers. Preliminary survey response data from 30 respondents was considered and analyzed separately for benefits and barriers. Demographic information of the respondents is





shown in fig 4.1 & 4.2. Cronbach's alpha test was performed for ensuring the reliability

Figure 4.1 Organization Type (Left) & Experience of respondents (Right) of the data. This test yielded α value of 0.930 for benefits and 0.937 for barriers, which shows highly reliable data was collected and used in this study.

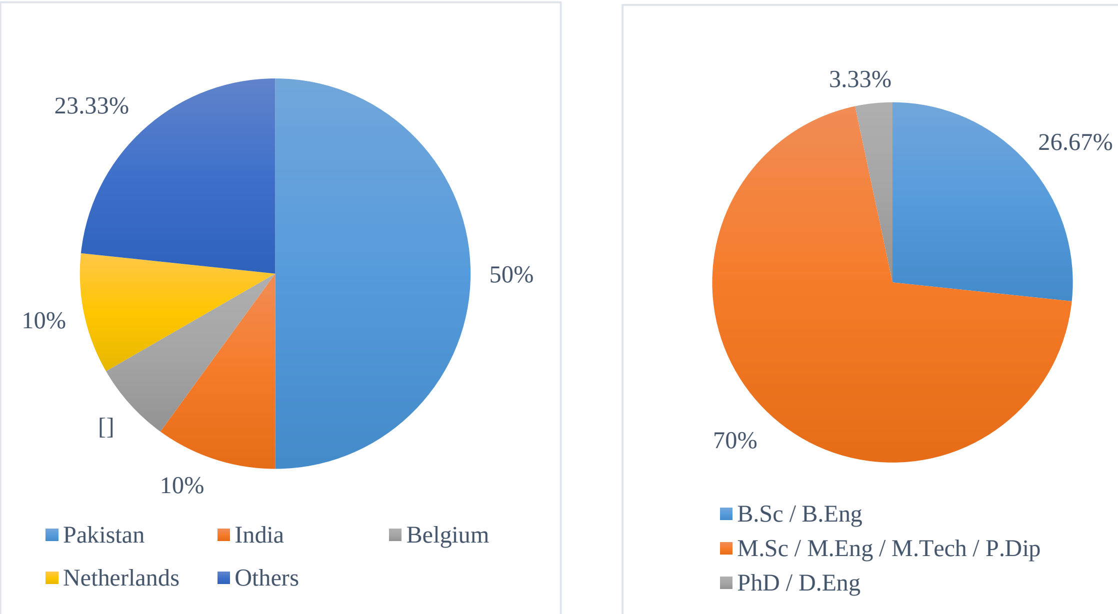


Figure 4.2 Country (Left) & academic qualification (Right) of respondents

Most of the benefits have high literature as well industrial score for example customization in design & façade of the buildings & reduction in construction time have almost similar ranks in both literature and industrial responses which means these are as important in the literature as in industry. However, some benefits like saving in construction cost & increased sustainability has high values for literature score but low for industry score which means these aren't that important for industry practitioners as compared to their importance in literature. Similarly, incorporation of further 3D Modelling tools and visual representation are more important in the opinion of industry professionals than literature. Therefore, after detailed analysis and testing, 60% - 40% combinations (60% weightage for the industry scores and 40% for literature scores) were used for calculation of combined final score. Benefits were ranked on the basis of their combined final score and combined significance of the benefits was calculated.

Table 4.3 shows the top 12 benefits having a combined significance of up to 60% were selected for further research.

Table 4.3 List of key benefits towards adoption of 3D printing in construction

Benefits / opportunities	**LS**	**IS**	**FS**	**Cum**
Customized homes & building and uniqueness in facade and other elements	0.0932	0.0438	0.0635	0.06
Reduction of construction time	0.0901	0.0416	0.0610	0.12
Reduced material waste	0.0838	0.0427	0.0591	0.18
Flexibility to the architects & novel shapes & design	0.0652	0.0438	0.0524	0.24
Increased sustainability	0.0714	0.0390	0.0520	0.29
Reduction of construction labor dependency & labor cost	0.0652	0.0427	0.0517	0.34
Saving in construction cost	0.0745	0.0350	0.0508	0.39
Environment friendly construction by using recycled material	0.0559	0.0383	0.0453	0.44
Improvement in productivity	0.0466	0.0427	0.0442	0.48

Safety in construction & remote area construction	0.0466	0.0412	0.0434	0.52
Printing the structure as a whole or in parts during disaster relief & rehab works	0.0373	0.0419	0.0401	0.56
In situ repair of construction areas with limited access	0.0435	0.0368	0.0395	0.60

Similar procedure was adopted for analysis of data collected against barriers towards adoption of 3D printing in construction industry. Top 18 barriers with a combined significance of up to 60% were selected and used for further research. The combined significance values for the selected barriers are as shown in table 4.4 below.

Table 4. 4List of key barriers towards adoption of 3D printing in construction

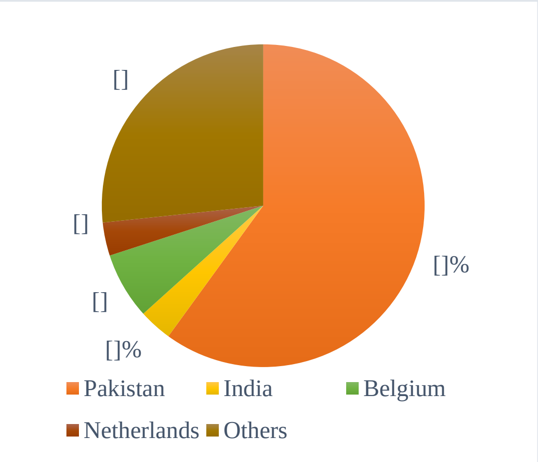
Barriers or challenges	**LS**	**IS**	**FS**	**Cum**
Lack of codes, guidelines & Regulations	0.0656	0.0360	0.0479	0.05
Unavailability of suitable materials	0.0750	0.0257	0.0454	0.09
High costs of 3D printers	0.0656	0.0295	0.0440	0.14
Quality related issues like void formation & rough surface finish	0.0594	0.0269	0.0399	0.18
Scale, size & weight etc. of 3D Printers	0.0531	0.0277	0.0380	0.21

Non compatibility with raw materials	0.0469	0.0266	0.0347	0.25
Precision of printed part still needs improvement	0.0375	0.0295	0.0327	0.28
Unsuitability of conventional design approach	0.0438	0.0251	0.0326	0.31
Economics of scale (for small enterprises, printer size etc.)	0.0375	0.0292	0.0325	0.35
Lack of research and knowledge	0.0313	0.0307	0.0309	0.38
Lower strength and testing procedures	0.0375	0.0254	0.0302	0.41
Printing complex structures	0.0313	0.0254	0.0277	0.44
Difficulties & uncertainties in calculation of final construction cost	0.0313	0.0251	0.0276	0.46
Low printing rate & productivity	0.0281	0.0271	0.0275	0.49
Lower Sustainability of 3D printed structure due weak bond b/w layers	0.0344	0.0227	0.0274	0.52
Resistance to changes and transformations & Lack of technical support	0.0250	0.0277	0.0266	0.55

Technology Readiness	0.0250	0.0274	0.0265	0.57
Lack of Organizational Support & Top management commitment	0.0156	0.0328	0.0259	0.60

4.4 Secondary Survey & Interviews

A detailed secondary data collection was carried out in the third phase of the study. Semi structure interviews and type-set questionnaires were used a data collection tool from local and international construction industry, respectively. Respondents from developing countries like Pakistan, India, China, Belgium etc. were contacted for collection of responses. Facebook, Linked-in, email, phone calls and one to one meeting were used as medium for data collection. Respondents were asked for recommendations and strategies for availing the benefits and reducing the impact of barriers towards adoption of 3D printing in construction industry of developing countries. Demographic information of the respondents is shown in Fig 4.3 below.



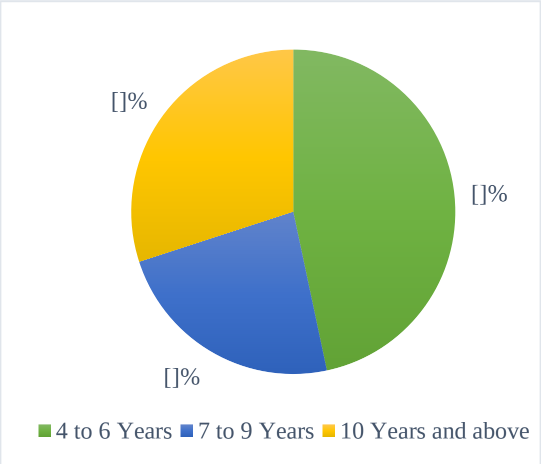


Figure 4.3 Country (Left) & Years of professional experience (Right)

Strategies and recommendations to enhance the effect of identified benefits from all the respondents were carefully listed down and frequencies of appearance of all identified strategies were recorded for each benefit separately. Frequency analysis was performed and normalized score for each strategy was calculated separately for against each benefit. Strategies were ranked on the basis of their normalized scores and cumulative normalized score was calculated for each strategy. Either top three strategies or strategies having a cumulative score of up to 60%, were selected for development of a roadmap towards adoption of 3D printing in construction industry of developing countries (Maria et al. 2019). The details of the selected recommendations against each benefit are shown in the table 4.5 below. The higher values and repetition for recommendations like visualization of the designs and models suggest that effect of benefits like customization in designs, sustainable designs options, uniqueness in façade and other elements can be optimized. High and repetitive recommendations for less involvement of human resource suggests, use of 3D printing will optimize benefits like reduction in construction time, material waste & cost, improvement in productivity and construction safety as discussed in literature (Anjum, Dongre et al. 2017, Panda, Tay et al. 2018). Ease of use of 3D printing as an automated process suggests to optimize benefits like printing complex structures, construction safety, flexibility to architects, novel shapes and design options, increased sustainable design options etc. Recommendations from the professionals show that some of the benefits are inter-related and increased effect of one benefit will optimize the other benefit as well for example less involvement of labor will address labor shortages, reduce the construction time and cost via reduced overheads, improve productivity and printing complex designs. Less wastage & reworks, less carbon emissions and use of new printers instead of old heavy machinery will optimize the effects of benefits like environment-friendly construction and high sustainability (Teymouri 2017). Less use of formwork and materials as per actual requirements was suggested as a lead to reduction in construction time, construction cost & paving way for environment – friendly construction.

Table 4.5 List of key strategies for availing the benefits towards adoption of 3D printing in construction

Benefit ID	Benefits and Opportunities	Recommendation	Norm Score	Cum Score
Be1	Customized homes & building and uniqueness in facade and other elements	Client will be able visualize the space, design & materials to be used which will help customization & user-friendly designs	0.18750	0.19
		Yes, its beneficial	0.14583	0.33
		It can print curved structures & complex designs	0.12500	0.46
		Blend of Client, Contractor, Designer & Architect	0.08333	0.54
		Aesthetics can be improved by using 3D Printing	0.06250	0.60
Be2	Reduction of construction time	No need for support and shuttering	0.17500	0.18

		&formwork etc for both onsite & offsite printing (Exclusion of activities)		
		Continuous work by robot & less involvement of human resource & human errors	0.15000	0.33
		Well planned process	0.12500	0.45
		Repetitive printing of same designs	0.10000	0.55
		Yes, its beneficial	0.10000	0.65
Be3	Reduced material waste	Exact model is printed on ground which lessen the material waste (material direct handled by printer & less onsite transportation is involved)	0.42857	0.43

		Proper coordination, less involvement of human resource, less errors & less rework results in reduced material waste	0.17143	0.60
		Yes, its beneficial	0.17143	0.77
Be4	Flexibility to the architects & novel shapes & design	No restrictions on created shapes especially decorative elements (any shape can be printed) (Printing complex structures) (Easy to print than construct)	0.31707	0.32
		Yes, It provides flexibility	0.19512	0.51
		Reduced Structural limitation and improved Constructability	0.09756	0.61

Be5	Increased sustainability	Use of recycled & reusable material e.g. plastic etc.	0.22857	0.23
		Sustainable construction is becoming a trend (Enhanced sustainable design option)	0.17143	0.40
		Less waste is produced & Less material is used	0.14286	0.54
Be6	Reduction of construction labor dependency & labor cost	Reduction in labor cost	0.29545	0.30
		Involvement of trained & skilled personnel	0.18182	0.48
		If 3D Printed is used in all stages (Easier to print than construct, mechanical process)	0.15909	0.60
Be7	Saving in construction cost	Reduction in material cost (e.g. less wastage, recycled material, no formwork)	0.21569	0.22

		Reduction in labor cost	0.17647	0.39
		It'll be costly	0.11765	0.51
		Reduced overheads	0.11765	0.63
Be8	Environment friendly construction by using recycled material	Use of green & recycle-able materials (reusable plastic or metallic material)	0.30000	0.30
		Definitely an advantage (less carbon emissions, less use of old machines)	0.27500	0.50
		Less rework & Wastage	0.20000	0.78
Be9	Improvement in productivity	Easy to print than construct	0.22727	0.23
		Increased productivity	0.20455	0.43
		Less rework due to errors	0.13636	0.57
Be10	Safety in construction & remote area construction	Yes, it'll be safe with reduced construction hazards	0.47059	0.47

		Use of robots and less human intervention	0.35294	0.82
		Add guides or guards on critical positions & wheels for movement	0.05882	0.88
Be11	Printing the structure as a whole or in parts during disaster relief & rehab works	Yes, definite advantage	0.24444	0.24
		Pre-printed modules for disaster struck areas, easy construction, reduced time, easy to print than construct	0.22222	0.47
		In parts, as technology is not developed to completely print a building	0.13333	0.60
Be12	In situ repair of construction areas with limited access	Possible solution for in-situ repair	0.25000	0.25
		Construction safety	0.16667	0.42
		Compatibility with existing structures	0.13889	0.56

		Not yet possible, smaller, portable & moveable robots e.g. drones	0.13889	0.69
		Easier to print than construct	0.13889	0.83

Similar procedure and analysis were applied on the responses collected for 18 identified barriers and strategies were ranked on the basis of their normalized scores. Minimum three strategies or strategies with a combined significance value up to 60% were selected for further analysis and development of roadmap towards adoption of 3D printing in construction industry of developing countries (Ahmed, Thaheem et al. 2019). The details of the selected recommendations against each barrier are shown in the table 4.6 below. Involvement of government bodies and development of regulations, use of locally available resources and continuous research & development appeared to be key recommendations for minimizing the effects of most of the barriers towards adoption of 3D Printing in construction of developing countries. AS 3D printing is still in its infancy, it'll required time, support from the industry and continuous research & development for successful adoption of 3D printing in construction.

Table 4.6 List of key strategies & recommendations for minimizing the effect of barriers towards adoption of 3D printing in construction

Barrier ID	**Barriers and Challenges**	**Recommendation**	**Norm Score**	**Cum Score**
Ba1		Involvement of government bodies and	0.3191	0.32

	Lack of codes, guidelines & Regulations	regulatory authorities e.g. PEC Council etc. for establishing rules & regulations		
		Funding & incentives for the research & development, adoption of the technology	0.1702	0.49
		Promotions of use of 3D printing via leaflets, advertisement, seminars, workshops etc	0.1489	0.64
Ba2	Unavailability of suitable materials	Use locally available & suitable materials after a little modification	0.2895	0.29
		New material through R & D, incentives for new developments	0.2895	0.58
		No, no alternate available, use already identified materials, import or technology transfer, (subsidies on taxation for import)	0.1579	0.74

Ba3	High costs of 3D printers	Repetitive printing & large-scale adoption e.g. housing projects will decrease the overall cost (Economics of scale)	0.2143	0.21
		Locally made 3D Printer via research & development	0.1429	0.36
		Offset by reduced construction time, saving in overheads	0.1429	0.50
		Supply & demand concept will decrease costs (Supply chain management)	0.1190	0.62
Ba4	Quality related issues like void formation & rough surface finish	Research & Development (Optimized and improved printers, codes & quality standards, material research for optimized mix / ratio etc.)	0.2564	0.26
		Quality assurance framework to be developed (via more Testing & Experimentation, Quality	0.2564	0.51

		control Engineers & Skilled operators should be employed)		
		Manually finishing the surface & refining the texture	0.2308	0.74
Ba5	Scale, size & weight etc. of 3D Printers	Research and development (Over time printers will scale up, modular printers)	0.4411	0.44
		As per requirement (Size & scale of the print / printer to be kept depending upon functionality & aesthetics)	0.2353	0.68
		Use light weight printers being used developed countries	0.1176	0.79
Ba6	Non compatibility with raw materials	Research & development of new material	0.3243	0.32
		Locally available Raw material can be used (Cement)	0.2703	0.59
		Yes, It should be addressed	0.1351	0.73
		Depends on the conditions	0.1351	0.86

Ba7	Precision of printed part still needs improvement	Continuous R & D and experiments for materials and printers	0.3095	0.31
		high precision can be achieved depending on setup & material	0.1667	0.48
		Yes, It should be addressed	0.1190	0.60
		Will be improved with time & Learning from past experience	0.1190	0.71
Ba8	Unsuitability of conventional design approach	Educating & training the architects & designers for development of new innovations, complex and energy efficient designs & approaches	0.3478	0.35
		Design to be integrated with academic research & testing, BIM & other design tools	0.1739	0.52
		Hiring the experts for new design approaches	0.1522	0.67
Ba9	Economics of scale (for small	Adoption of technology on large scale by larger	0.2702	0.27

	enterprises, printer size etc.)	companies to offset the cost (Initially)		
		3D printers are too costly	0.1351	0.41
		Financial Support & funding by govt. & governing bodies	0.1351	0.54
Ba10	Lack of research and knowledge	Continuous research & development on 3D Printing (enhanced over last couple of years)	0.4103	0.41
		Raising awareness (Organize demonstrations & industrial conferences, incorporate learning courses, trainings & seminars)	0.3077	0.72
		Increased research budgets and incentives	0.1795	0.90
Ba11	Lower strength and testing procedures	Testing procedures & availability of apparatus should be established	0.2727	0.27
		Compressive strength is not an issue, sometimes more than concrete	0.2045	0.48

		Incorporate reinforcement for increasing tensile strength	0.1136	0.59
Ba12	Printing complex structures	Research & innovation for more advanced printers	0.2188	0.2188
		Can be printed	0.1875	0.4063
		Combination of sound architectural design skills and 3D Printing is necessary (more details & expert consultant is required)	0.1875	0.5938
Ba13	Difficulties & uncertainties in calculation of final construction cost	Previous projects as a case study for predicting final cost, more printing	0.4211	0.42
		Experimental studies for calculation, use PERT & establish algorithms for calculation, prototypes	0.1579	0.58
		Cost is easier to determine as uncertainties of conventional construction are eliminated	0.1316	0.71

Ba14	Low printing rate & productivity	Research & development on materials & printers	0.2581	0.26
		Depends on type of printer being used but it can continuously print and offset this effect (Design compatibility with available printers)	0.258!	0.52
		Design might take time, but printing will offset	0.0968	0.61
Ba15	Lower Sustainability of 3D printed structure due weak bond b/w layers	Research & development	0.1778	0.18
		It should be rectified	0.1556	0.33
		Use of materials with good mechanical properties	0.1556	0.49
		Provision of Reinforcements like Steel, mixed reinforcers like fiber glass, polypropylene fiber etc	0.1111	0.6
Ba16	Resistance to changes and transformations	Training & active industrial participation (More awareness)	0.2500	0.25

	&Lack of technical support	This issue will be resolved with the passage of time	0.1667	0.42
		Lack of standards is stopping large group of companies from adopting 3D printing	0.1389	0.56
		Govt should encourage local adoption & production (incentives)	0.1389	0.69
Ba17	Technology Readiness	Still maturing, will need time	0.4250	0.43
		Promotion on Govt Level (funding, advertisement, awareness, education)	0.1500	0.58
		Research and development	0.1250	0.70
Ba18	Lack of Organizational Support & Top management commitment	Awareness campaigns and trainings	0.2750	0.28
		Support & coordination is necessary for new and innovative technologies	0.1500	0.43
		Incentives from Governments	0.1500	0.58

4.4 Roadmap towards adoption of 3D Printing in Building & Construction Industry of Developing Countries

Above mentioned recommendations were used to establish the strategies and a roadmap towards adoption of 3D Printing in construction industry of developing countries.

1) Involvement of the government bodies is essential for successful adoption of 3D printing in construction, development of rules, regulations and guideline. Governments can support 3D Printing in construction by initiating incentive programs for firms & individuals. Provision of funds and tax subsidies can also enhance the chances of adoption of 3D printing on vast scale.
2) Foreign investors and 3D printer manufacturers should be encouraged to invest in construction industry by the government.
3) Continuous research and development is required to be conducted with the close collaboration of industry and academia.
4) Awareness campaigns and seminars should be held for creating awareness in public towards possible use of 3D printing in construction. Demand of the potential clients will increase the supplies and result in successful adoption of 3D printing.
5) Training programs and workshops should be held on regular basis for increasing the awareness and knowledge of the organizations and experts.
6) Potential benefits and opportunities should be spread out via Higher education institutes and courses should be incorporated in curriculum of different degree awarding institutes
7) Mass printing should be adopted on a larger scale for decreasing the upfront cost of the 3D printers and local printers should be developed and designed as per locally

available resources. Low cost housing can be a potential area of application for the 3D printing

8) Onsite and offsite printing should be encouraged in disaster relief activities as it will save time and human resource. Also, due to availability of permanent structures relocation problems can be avoided in case of such calamities
9) 3D Printing should be used for reproducing the damaged parts of historical buildings and In-situ repairs to the parts where human access isn’t possible
10) Experimental studies and previous project data should be used for better estimation of the final cost of 3D printing
11) 3D printing should be initially adopted for printing complex designs and unique façade elements. High initial costs can be offset by providing customized designs.
12) Use of 3D printing along with conventional construction processes should be encouraged as it will save time & cost.

Chapter 5

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

The study is concluded in this chapter by covering & summarizing the research results & findings and stating the recommendations for future research. The insight will help the reader to understand the crux of the study and parting ways for future endeavors related to this area of research.

5.2 Conclusions

Construction industry is unable to meet the accommodation requirements of the rapidly growing population of the developing countries. Technology adoption is inevitable to increase the productivity, reduce time and cost of the Construction projects. 3D printing is one of the emerging technologies as a mode of total automation in construction industry of developed countries. Researchers are working on the adoption of 3D printing technology in construction industry. This study thoroughly reviewed the published literature on the subject. For this purpose, key benefits and barriers towards adoption of 3D printing in construction industry were identified through literature review and preliminary survey. After identification of these factors, secondary data collection was performed and recommendations for optimizing the effects of key benefits and barriers were collected from respondents via Interviews and type-set questionnaires. The top recommendations were used for development of a roadmap towards adoption of 3D printing in construction industry of developing countries. The final roadmap can provide guidance to the industry professional on how to successfully adopt 3D printing in construction industry. This study contributes to the existing body of knowledge by focusing on adoption of 3D printing in construction industry of developing countries and opens the window towards future research in this area. However, this study only covers the adoption of 3D printing on building & construction projects.

5.3 Recommendations

Research can be carried out for development of a framework or technology adoption models on real time projects. Research on development of 3D Printing materials and local production of 3D printers can be carried out in developing countries. This research might prove as a trigger towards real time application of this technology on the construction projects of country like ours.

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Annexure – I

Challenges and Opportunities towards adoption of 3D Printing in Building & Construction Industry of Developing Countries

Dear Sir/Madam,

This survey is being carried out as part of MS research titled "A framework towards adoption of 3D Printing in building & construction industry of developing countries". The research aims at developing a framework towards adoption of 3D Printing in construction. This elementary survey will help to identify the most important challenges and benefits that might help in decisions related to adoption of 3D Printing.

Your contribution towards this research is highly appreciated. Please be assured that the data will only be used for study purpose and no personal information will be disclosed at any forum/level.

Please click next to continue and complete the survey and remember to click submit at the end. In case of any inquiry, please feel free to contact.

Regards
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*Required

Personal Information

1. Please indicates your highest academic qualification.
   - B.Sc/B.Eng
   - M.Sc/M.Eng/M.Tech/P.Dip
   - PhD/D.Eng

2. Please indicate your years of professional experience
   - From 0 to 1
   - From 1 to 3
   - From 4 to 6
   - From 7 to 9
   - 10years or more

3. Please indicate your field of work (Please select all that may apply).
    - Architecture
    - Building Design
    - Infrastructure Management
    - Construction Management
    - Quantity Surveying
    - Facility Management
    - Site Execution
    - Project Management
    - Other (Please specify): _____________

4. Please indicate your job title.
    - Project Director
    - Project Manager
    - Construction Manager
    - Contract Administrator
    - Assistant Manager
    - Site Manager
    - Project Engineer
    - Architect/Designer
    - Consultant
    - Academician
    - Other (Please specify): _____________

5. Type of organization.
    - Client
    - Consultant
    - Contractor
    - Academia
    - Other (Please specify): _____________

6. Country (Please select your country from drop down list).

Benefits of 3D Printing in Construction

Question: To what extent adoption of 3D Printing benefits these factors in construction industry.

Scale:**0** = No effect **1** = Very low **2** = Low **3** = Medium **4** = High **5** = Very high

Mark only one box per row.

Factors	0	1	2	3	4	5
Reduction in construction time						
Saving in construction cost						
Reduction in cost variations due to lesser change orders						
Improved quality						
Strength and durability of 3D Printed Houses						
Visual representation						
Increased sustainability						
Use of recycled materials						
Gain in thermal insulation performance						
Reduction of labor dependency & labor cost						
Safer and genderless working conditions (Cultural Shift)						
Reduced material waste						
Customized homes & buildings (uniqueness in façade & other elements)						
Flexibility to architects (Novel shapes & designs)						
In-situ repairs of construction areas with limited access						
Printing of a complete structure or its parts during disaster relief and rehab works						
Construction on other planets (like Colonization on Mars, Moon etc)						
Restoration and refurbishment of damaged parts of historical buildings						
Improvement in productivity						
Safety in construction (e.g. construction in remote areas)						
Further incorporation of 3D Computer Modelling e.g. 3D CAD, BIM etc						
Ease of use						
Automation in construction and hybridization with the conventional processes						
High end technology-based job creation						
Better workflow management						

Challenges towards adoption of 3D Printing

Question: To what extent the following challenges & barriers can affect the adoption of 3D Printing in building & construction Industry.

Scale:**0** = No effect **1** = Very low **2** = Low **3** = Medium **4** = High **5** = Very high

Mark only one box per row.

Challenges / Barriers	**0**	**1**	**2**	**3**	**4**	**5**
Low printing rates of 3D Printer						
High cost of 3D Printers						
Economics of scale (for small sized enterprises, size of printers etc.)						
Difficulties & uncertainties in calculation of final construction cost						
Quality related issues like void formation & rough surface finish						
Precision of printed parts						
Lower sustainability of structure due to weaker bond between the layers						
Requirement of thinner layers for high resolution which is time consuming						
Maintenance issues due to high level of abrasiveness of concrete						
Unavailability of suitable materials						
Non compatibility with raw materials						
Lower strength and testing procedures						
Anisotropic properties of materials						
Difficulties in material change-over						
Lack of codes, guidelines and regulations						
Lack of research and knowledge						
Lack of organizational support & top management commitment						
Managerial issues						
Negative social impacts like unemployment due to fully automated system						
Intellectual property and patent related issues						
Scale, size & weight of 3D Printers						
Printing of complex structures						
Technology readiness						
Transportation of equipment and prefab printed parts						
Resistance to changes and lack of technical support						
Requirement of support structures						
Technology transfer and lack of skilled personnel						
Compatibility with work packages						
Unsuitable printing & fabrication technology						

Fear and responsibility of failure						
Active control of rheology and stiffening						
Lack of successful cases						
Unsuitability of conventional design approach						
Huge gaps between architectural ideas and real time printing / manufacturing						
Divergence from design to execution						
Requirement of 3D Digital Models						
End User acceptability						

Annexure – II

A roadmap towards adoption of 3D Printing in Building & Construction Industry of Developing Countries

Respected Sir/Madam,

This interview is being carried out as part of MS research titled "A roadmap towards adoption of 3D Printing in building & construction industry of developing countries". The research aims at providing a roadmap towards adoption of 3D Printing in construction. Key benefits and barriers were identified through a combined literature and industry response score. Responses to questionnaire surveys were collected from industry professionals on a Likert scale of 0 to 5 against each factor. After detailed analysis 12 benefits and 18 barriers were selected for interviews & further analysis. This interview will help in decision making & provision of a roadmap towards adoption of 3D Printing in Construction.

Your contribution towards this research is highly appreciated. Please be assured that the data will only be used for study purpose and no personal information will be disclosed at any forum/level.

Regards
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Islamabad, Pakistan
Email: **mshah.cem16nit@student.nust.edu.pk**

Personal Information

Sr. No	Description	Answers
1	Respondent's Name	
2	Highest Academic Qualification*	
3	Years of Professional Experience*	
4	Job Title	
5	Type of Organization*	
6	Name of Organization	

7	Contact Info (Email ID or Phone Number) *	
8	Country*	

Benefits & Opportunities of 3D Printing in Construction

Question: How do you think, the effect of these benefits (toward adoption of 3D Printing in construction industry) can be optimized?

Sr. No	Benefit / Opportunity	Recommendation
1	Customized homes & building and Uniqueness in façade and other elements	
2	Reduction of Construction Time	
3	Reduced Material Waste	
4	Flexibility to the Architects & Novel Shapes & Design	
5	Increased Sustainability	
6	Reduction of construction labor dependency & labor cost	
7	Saving in Construction cost	
8	Environmental- Friendly Construction by using Recycled Material	
9	Improvement in productivity	

10	Safety in construction & remote area construction	
11	Printing the structure as a whole or in parts during disaster relief & rehab works	
12	In situ repair of construction areas with limited access	

Challenges & Barriers towards adoption of 3D Printing

Question: How do you think, the effect of these barriers (toward adoption of 3D Printing in Construction Industry) can be negated?

Sr. No	Barriers / Challenges	Recommendation
1	Lack of Codes, guidelines & Regulations	
2	Unavailability of suitable materials	
3	High Costs of 3D Printers	
4	Quality related issues like void formation & rough surface finish	
5	Scale, size & weight etc of 3D Printers	
6	Non compatibility with raw materials	

7	Precision of Printed part still needs improvement	
8	Unsuitability of Conventional Design approach	
9	Economics of scale (for small enterprises, printer size etc.)	
10	Lack of Research and Knowledge	
11	Lower Strength and testing procedures	
12	Printing complex structures	
13	Difficulties & uncertainties in calculation of final construction cost	
14	Low Printing Rate & Productivity	
15	Lower Sustainability of 3D Printed Structure due weak bond between layers	
16	Resistance to changes and transformations & Lack of technical support	
17	Technology Readiness	
18	Lack of Organizational Support & Top management commitment	