Exploring the Adoption of 3D Printing for Reducing Capital and Operational Costs of Façades in Office Buildings

استكشاف اعتماد الطباعة ثلاثية الأبعاد لتقليل التكاليف الرأسمالية والتشغيلية للواجهات في مباني المكاتب

by

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ABSTRACT

The construction sector is one of the most important sectors worldwide today. Everyday lives of humans revolve around the use of infrastructure and buildings that are created by construction companies hence their importance in society today. For a long time, people have taken for granted the technologies or innovations that they use today and hardly try to dig into the people or companies behind the innovations. For several years, people have described the construction industry as conservative because of its reluctance and delay in adopting new technology. In fact, others largely view the construction industry as regressive in light of other industries such as automobile and manufacturing. What people fail to take into consideration is the complexity of the construction process that has driven away several personnel who initially had the interest of working in the sector. However, the construction industry is warming up to 3D printing technology that could have numerous benefits to the sector. The main purpose of this qualitative research is to explore 3D printing components and understand how they can impact the capital and operational cost of a façade of an office building.

This research relies on both primary and secondary data sources. Various literatures serve as the secondary sources of data while primary data is collected through interviews with participants with knowledge of 3D printing and who have previously used or who currently use 3D printing technology in the construction sector. The reviews and the research findings indicate that 3D printing components lead to a reduction in the capital and operational cost.

A major limitation of this study is that it mainly focused on participants with knowledge on 3D printing or who have worked with or are currently using 3D printing technology in the construction sector within Dubai. Also, the study focused on a limited number of participants. Thus, future studies should focus on collecting data from more participants to ensure validity and accuracy of results.

Keywords: 3D printing technology, durability, usability, applicability, maintainability, replacement, maintenance, capital cost, operational cost.

الملخص

يعد قطاع البناء أحد أهم القطاعات في العالم اليوم. الحياة اليومية للبشر تدور حول استخدام البنية التحتية والمباني التي تم إنشاؤها من قبل شركات البناء وبالتالي أهميتها في المجتمع اليوم. لفترة طويلة، اعتاد الناس على التقنيات أو الابتكارات التي يستخدمونها اليوم ولا يكادون يحاولون البحث عن الأشخاص أو الشركات التي تقف وراء هذه الابتكارات. منذ عدة سنوات، وصف الناس صناعة البناء والتشييد بأنها محافظة بسبب ترددها وتأخيرها في تبني تكنولوجيا جديدة. في الواقع، ينظر آخرون إلى حد كبير إلى صناعة البناء والتراجع في ضوء الصناعات الأخرى مثل السيارات والتصنيع. ما يفشل الناس في أخذه في الاعتبار هو تعقيد عملية البناء التي أبعدت العديد من الموظفين الذين أبدوا اهتمامهم في البداية بالعمل في هذا القطاع. ومع ذلك، فإن صناعة الإنشاءات تعمل على تطوير تقنية الطباعة ثلاثية الأبعاد التي يمكن أن يكون لها فوائد عديدة للقطاع. الغرض الرئيسي من هذا البحث النوعي هو استكشاف مكونات الطباعة ثلاثية الأبعاد وفهم كيفية تأثيرها على التكلفة الرأسمالية والتشغيلية لواجهة مبنى المكاتب.

يعتمد هذا البحث على مصادر البيانات الأولية والثانوية. تعد الأدب المتنوع بمثابة المصادر الثانوية للبيانات بينما يتم جمع البيانات الأولية من خلال المقابلات مع المشاركين الذين لديهم معرفة بالطباعة ثلاثية الأبعاد والذين استخدموا أو يستخدمون تقنية الطباعة ثلاثية الأبعاد في الوقت الحالي في قطاع البناء. تشير المراجعات ونتائج البحوث إلى أن مكونات الطباعة ثلاثية الأبعاد تؤدي إلى انخفاض في التكلفة الرأسمالية والتشغيلية.

يتمثل أحد القيود الرئيسية لهذه الدراسة في أنها تركز بشكل أساسي على المشاركين ذوي المعرفة بالطباعة ثلاثية الأبعاد أو الذين عملوا مع تقنية الطباعة ثلاثية الأبعاد أو يستخدمونها حاليًا في قطاع البناء داخل دبي. أيضا، ركزت الدراسة على عدد محدود من المشاركين. وبالتالي، ينبغي أن تركز الدراسات المستقبلية على جمع البيانات من عدد أكبر من المشاركين لضمان صحة ودقة النتائج.

الكلمات المفتاحية: تكنولوجيا الطباعة ثلاثية الأبعاد، المتانة، قابلية الاستخدام، قابلية التطبيق، الصيانة، الاستبدال، التكلفة الرأسمالية، التكلفة التشغيلية.

DEDICATION

I dedicate this book to my beloved parents, siblings, and family for their unlimited support.

A special dedication is to my mother who has dedicated to filling my life with love and inspiration.

To my Supervisor and dear friends whom were a source of inspiration and encouragement, without you this dissertation might not have been completed

Thank you all
For your love and support

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List of Abbreviation

3DP	3D Printing
AM	Additive Manufacturing
CC	Contour Crafting
CMU	Concrete Masonry Unit
EBM	Electron Beam Melting
FDM	Fused Deposition Modeling
LOM	Laminated Objective Manufacturing
RP	Rapid Prototyping
SL	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
UAE	United Arab Emirates
UV	Ultraviolet

CHAPTER 1- INTRODUCTION

1.1 Introduction

This chapter gives an overview or background of 3D printing technology and its use in the construction industry, which is the focus of this research. It also presents or analyzes the research problem, highlights the significance of the research, scope of the research and limitations, aims and objectives of the study, the research question, and the dissertation layout.

1.2 Background of the Research

According to Camacho et al. (2017), the construction sector is one of the most important sectors worldwide today. Everyday lives of humans revolve around the use of infrastructure and buildings that are created by construction companies hence their importance in society today (Camacho et al., 2017). For a long time, people have taken for granted the technologies or innovations that they use today and hardly try to dig into the people or companies behind the innovations. For several years, people have described the construction industry as conservative because of its reluctance and delay in adopting new technology. In fact, others largely view the construction industry as regressive in light of other industries such as automobile and manufacturing (Skold and Vidarsson, 2015). What people fail to take into consideration is the complexity of the construction process that has driven away several personnel who initially had the interest of working in the sector.

However, in recent years, the face of the construction industry is changing because of the gradual adoption of a new technology known as 3D printing. This technology has attracted the attention of many players in the global construction industry in recent years

(Canas, 2014). Also referred to as 3DP, this technology is fast and less expensive as compared to the construction models currently in use. For the construction sector, 3D printing technology presents a number of opportunities and benefits. Unfortunately, the applicability and implication of 3D printing for the construction industry is yet to be explored by studies, and this is what this study seeks to explore. Without doubt, this technology ought to be embraced by constructions firms to become more efficient and add more value to customers (Skold and Vidarsson, 2015).

1.3 Problem Analysis

According to WinSun's article "Demonstrating the Viability of 3D Printing at Construction Scale," one of the major challenges faced by the global construction sector today is the entrenchment of traditional processes that are largely unecological and unproductive (World Economic Forum). The article acknowledges that it is unfortunate that the construction industry despite how important it is, has hardly changed throughout history. Many of the vertical construction projects around the world are carried out by workmen who are required to add layers of building materials on top of one another. These traditional approaches should be shunned in the modern times where technology is taking center stage. Traditional construction models tend to result in low productivity (World Economic Forum). Also, traditional construction models rely heavily on the skills of individuals. The huge number personnel involved in traditional construction models as well as the increased wastage of materials and resources has increased the capital and operational costs of construction projects that rely on these models (World Economic Forum). With these challenges, a perfect solution remains a fast shift to 3D printing technology that is likely to

have an impact on the capital and operational cost in the construction industry, particularly for a façade of an office building.

1.4 Research Significance

This study provides an exciting opportunity to advance our knowledge of 3D printing. It also offers some important insights into various types of 3D printing technologies and how they are used or operate. It also focuses on various characteristics of 3D printed components such as durability, usability, applicability, and maintainability that significantly impact the capital and operational cost of a façade of an office building and various projects in the construction industry.

1.5 Scope and Limitations of Research

The focus of this dissertation is on the impact of 3D printing components on the capital and operational cost of façade of an office building based in Dubai, UAE. The research will collect views of a number of individuals with knowledge on 3D printing technology and who have previously or who currently use the technology particularly in the construction sector. The participants who will give their views on the problem will be from Dubai. Moreover, this research aims to convince every player in the UAE's construction industry on the importance of shunning tradition models of construction for the new 3D printing technology. The focus of this research will be mainly on Dubai meaning that other participants or areas will be out of the scope, which is a major limitation of this research.

1.6 Aims and Objectives of the Study

This research will explore the usage of 3d printing components in reducing the capital cost and operational cost of a façade of an office building. This aim is achieved through the following objectives:

- to investigate the 3d printing technology usage in producing 3d components for a façade
- to investigate how 3d printing can reduce capital cost
- to investigate how 3d printing can reduce maintenance cost
- to seek the opinion of experts on 3d printing with a view to reduce capital and operation cost

1.7 Research Question

This research focuses on the impact of 3D printing components on the capital and operational cost of a façade of an office building. Thus, this paper will attempt to answer the following question:

- Can 3D printing reduce the capital and operational cost of a façade of an office building?

1.8 Dissertation Layout

The layout of this dissertation is as follows:

Chapter One: presents a background of the research, problem analysis, research significance, scope of the research and limitations, aim and objectives of the study, and research question.

Chapter Two: presents a review of related literature and studies that explore the application and impact of 3D printing technology in the construction industry.

Chapter Three: presents the methodology used in the research and entails the research philosophy, research strategy, research design, data collection, interview protocols, and data analysis.

Chapter Four: explores the data collected during research and is based on two major prospects of the impact of 3D printing components on capital cost and the impact of 3D printing components on operational cost.

Chapter Five: presents a discussion and conclusion to highlight the major findings of the impact of 3D printing components on the capital and operational cost of a façade of an office building. It also presents the research conclusion, research implications, limitations, further research recommendations, and research knowledge contribution.

CHAPTER 2- LITERATURE REVIEW

2.1 Introduction

This chapter captures, summarizes, and reviews relevant literature that alongside the empirical illustration will be critical for the analysis and fulfilment of the dissertation's purpose. The literature review consists of seven areas including innovation and technical development in the construction industry, the history of 3D printing technology in the construction industry, the technology of 3D printing and its use in the construction industry, the benefits of 3D printing technology on capital cost in the construction industry, characteristics of 3D printing components in building (façade of office buildings), capital cost of 3D printing compared to traditional models in the construction industry, and operational cost of 3D printing compared to traditional models in construction.

2.2 Innovation and Technical Development in the Construction Industry

Skold and Vidarsson (2015) argue that for a long time, the construction industry has been criticized for its lack of innovation and technical development that has seen it remain behind in terms of competitiveness. The term innovation has been defined differently in various contexts. However, a generally agreed definition of innovation is that it is a process involving how ideas, artefacts, and practices are generated, adopted, implemented, and incorporated within an organization. The crucial role played by the construction industry in society today cannot be ignored. Most of the day-to-day human activities can only be undertaken because of the infrastructure in place thanks to the construction sector. This notwithstanding, it is important for the sector to adopt innovations that can help to develop a competitive strategy in the end (Sobotka and Pacewicz, 2016). The low level of innovation

in the construction industry has contributed to the sector's low development and performance in terms of quality, product functionality, and productivity. According to Skold and Vidarsson (2015), that there has been no innovation in the construction industry is not an issue of concern. The issue of concern is that most of the innovations in place focus more on product enhancement rather than process improvement. The structural features coupled with the characteristics of construction projects have also played a role in the relatively low level of innovation in the construction sector. Structural features in the construction industry such as complexity, immobility, costliness, and durability are in jeopardy. This alongside informal coordination and decentralized decision-making have hampered innovative evolution in the construction industry.

The adversarial characteristic of relations in the construction sector has also contributed in one way or the other to the relatively low level of innovation in the construction sector. The poor relationships among personnel have set the stage for the lack of collaboration among parties in the construction industry. This, in turn, leads to many innovation initiatives focusing on single projects thus creating discontinuity when it comes to the development of knowledge and how this should be transferred from project to project. This is a big challenge for construction projects that are complex and large. A characteristic of construction projects is that they require a considerable amount of problem-solving as the techniques and technologies that are used must be in line with the specific construction situation. This is important when it comes to meeting the needs of clients in relation to the construction site constraints. Skold and Vidarsson (2015) opine that in as much as there could be a degree of innovation in construction projects, problem-solving characteristics are often evident. It is in

such situations that a perfect solution such as adopting new innovations could help avert these challenges.

According to Skold and Vidarsson (2015), the adoption of new technologies or innovations such as 3D printing in the construction industry is influenced by various factors. In their exploration of the factors that influence the adoption of innovations such as 3D printing technology in the construction industry, Skold and Vidarsson (2015) identify six different factors including clients and manufacturing firms, the structure of production, industry relationships, procurement systems, regulations or standards, and organizational resources. In terms of clients and manufacturing firms, the fact that clients demand and pressurize project owners to improve the quality, flexibility, durability, and overall characteristics of construction projects paves the way for the adoption of innovation such as 3D technology. Skold and Vidarsson (2015) presume that the more demanding and pressurizing clients are, the higher the likelihood for innovativeness in construction projects. In addition to clients, manufacturing firms can heighten knowledge to be applied in construction projects thus paving the way for increased innovativeness. In terms of the structure of production, various factors are involved thereby impacting the adoption of innovation in construction projects. Skold and Vidarsson (2015) argue that the expectation of durability of construction projects forces parties involved to use tried and tested techniques to achieve this object. This means that the opportunity of using new or modern innovations such as 3D printing technology is shunned. Another factor associated with the structure of production is the durability that puts pressure on suppliers to have or keep spares far into the future thus preventing manufacturers from changing their range of products. Also associated with the factor of the structure of production is the fact that small construction businesses are

predominant in the construction industry and they have limited resources required to facilitate the adoption of innovation in the industry.

The third factor that influences the adoption of innovations in the construction industry at least according to Skold and Vidarsson (2015) is industry relationships. Common in the construction industry are loose and temporary relationships between parties involved in construction projects. Once existing relationships are dissolved, the adoption of innovation becomes difficult. Notably, tight or strong relationships among participants in construction projects are likely to increase the chances of not only adopting specific innovations but also transferring them from one project to another. When it comes to procurement systems, innovativeness in the construction industry is highly likely if more innovative procurement methods are in place. Some of these methods include partnering as well as fixed cost contracts that can help in the improvement of communication and learning in the procurement process. To increase their chances of becoming more innovative and adopting new technologies such as 3D printing, companies involved in construction should focus more on partnering and alliancing on the supply-side rather than competitive tendering. Concerning regulations or standards, there is no doubt that regulations or policies put in place by governments can hamper the adoption of new technologies in the construction industry. Regulators focus on coming up with rules that are fair to the market, and their basis is on aspects such as industry structure, organizational competencies, market conditions, competition, advanced practices, and technologies, as well as technical infrastructure. These and the lack of knowledge can see regulators stress on the use of old technologies at the expense of new technologies such as 3D printing in the construction industry (Skold and Vidarsson, 2015). The organizational resource is the final and most important factor

influencing the adoption of innovation in the construction sector. A construction company with no culture of innovation, no innovation strategy, and no knowledge codification can hardly push for innovativeness in the context of construction. This means that new technologies such as 3D printing can hardly be embraced and implemented by such organizations.

2.3 History of 3D Printing Technology In the Construction Industry

According to Canas (2014), the history of 3D printing can be traced to the 1980s when Charles W. Hull created the first working 3D printer. In the 1980s, 3D printing technology was expensive and could not be used in viable commercial applications. Several decades later, 3D printing is at the center of applications and other mechanisms used by engineers and designers in their line of duty. Canas (2014) argues that with the widespread adoption of 3D printing technology, several sectors such as the construction sector have benefited greatly from the same. In the modern world, 3D printing technology has become relatively less expensive, affordable, and can work in a variety of materials or applications. The technology has since undergone evolution and is currently being used widely in the construction industry.

Wu, Wang, and Wang (2016) outline that the use of 3D printing has been adopted in other sectors other than the biomedical and manufacturing sectors. In the manufacturing sector, for instance, 3D printing technology was used in the production of prototypes with small part sizes, low production volumes, and complex designs. At the time, 3D printing was widely referred to as Rapid Prototyping (RP). Wu, Wang, and Wang (2016) also mention that stereolithography was used in the development of the first 3D printer by Charles Hull in 1984. In the subsequent years, however, there have been major developments to the

technology given the development of both FDM and SLS in 1989. There have been several attempts over the years to use the technology in the construction industry. Wu, Wang, and Wang (2016) opine that 3D printing was later used in the production of construction-related materials, a move that demonstrated the viability and applicability of the technology in the construction industry. Some of the attempts to use the technology in the construction industry included the use of stereolithography in the production of ceramic three-dimensional parts. With improvements in technology, there has been the expansion of the use of 3D printing in the output of construction-related materials other than ceramic products (Camacho et al., 2017) Today, for instance, 3D printing technology is used in the production of nylon and plastic materials that are used in building projects as window frame fixtures, plug fixtures, and plumbing fittings. There is also the element of concrete printing that has shown feasibility when it comes to the printing of geometrically complicated concrete products.

Wu, Wang, and Wang (2016) also share the idea of 3D printing and architectural models. They aver that the adoption of 3D printing in the production of architectural models came in the early 2000s. Several years later, some 3D printing technologies have been used and tested for stability when it comes to printing architectural models. The use of 3D printing in the construction industry has gradually shifted focus to entire building projects in recent years. An example is in 2014 when a company known as WinSun, located in China, successfully printed several houses in less than a day in Shanghai, China. Another case is that of Qindao Unique Technology that used the 3D printing technology to construct houses in 2014. The company's 3D printer relies primarily on the FDM technology that deposits and stacks half-melted printing material from one layer to another.

Head (2017) also gives an overview of the history of 3D printing in the construction industry in her article "A History of 3D Printing in Construction & What You Need to Know." She believes that 3D printing is without a doubt a revolutionary technology in the construction industry. According to Head, the beginning or inception of 3D printing technology can be traced to the 1980s when Charles "Chuck" Hull invented the stereolithography (SLA) in 1984. The article describes the SLA as a method pf 3D printing whereby designers create a 3D model, which is then printed layer by layer into a solid physical object. SLA as a 3D printing technique primarily involves pointing a UV laser toward a liquid photopolymer that is charged with making it solid. Head (2017) argues that SLA printers are the most commonly used 3D printers in the construction industry as well. With the knowledge that 3D printing technology would be used in a range of sectors, Charles Hull founded 3D Systems by taking out some patents. Hull's 3D System is a 3D printing company that has been operational over the years and still exists today. Head (2017) further mentions that one of the earliest uses of 3D printing in the construction sector was the printing of tabletop scale models for architecture firms. The tabletop scale models played a crucial role in the designing process and were considered valuable when it came to selling and planning building projects. With 3D printing technology, the erection of the scaled-down models was relatively cheaper and easier as compared to the traditional hand-crafted replicas that were time-intensive.

According to Head (2017), with the inception of 3D printing technology, it became unnecessary for construction firms to create physical models when undertaking construction projects. However, the physical models are still used today alongside the 3D printing technology in the construction industry. In the 1990s, a number of organizations in the

construction industry started to experiment with the use of 3D printing technology, particularly in the production of modular components of full-scale projects. The applications were fully adopted in the construction industry by the 2000s resulting in the transformation of the industry as a whole. There has been full-scale practical application of 3D printing technology in the construction industry from 2000 to the present (Head, 2017). What is surprising is that 3D printing capabilities have undergone rapid expansion and growth in the past few years despite being unthinkable 15-16 years ago. Head (2017) mentions a number of cases in the construction industry where 3D printing technology has not only been used but has also been successful. She mentions the Contour Crafting System that was unveiled in 2006 by Dr. Behrokh Khoshnevis of the University of Southern California. The Contour Crafting System is a huge 3D printer that is used in the printing of buildings. It operates like a desktop 3D printer although it utilizes a crane for the printing purposes and relies on concrete as the medium when it comes to laying down the structural elements of a building. The Contour Crafting System is illustrated below.

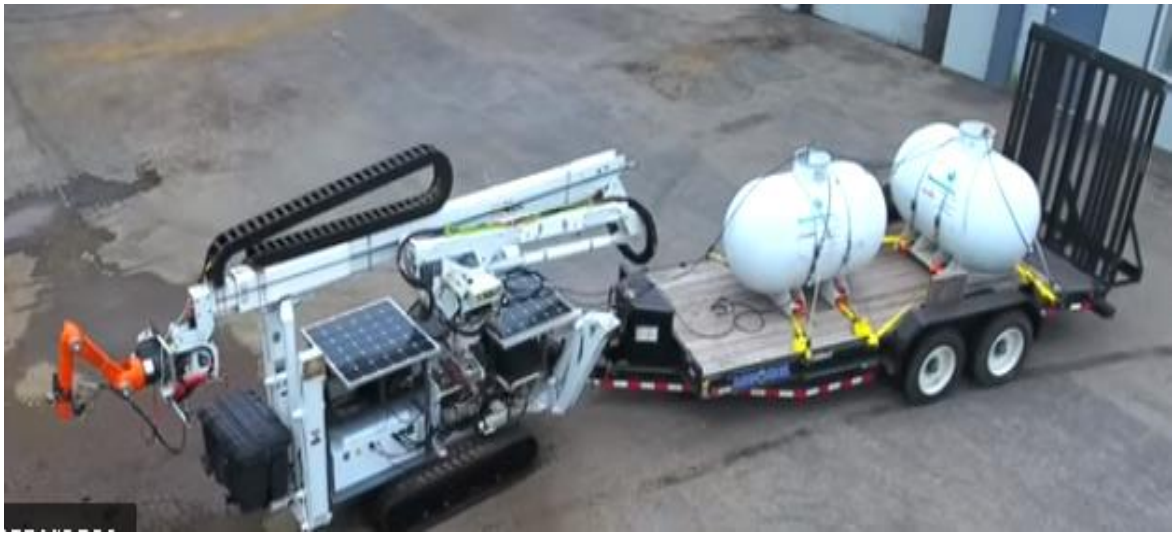

Figure 1: The Contour Crafting System (Head, 2017)

Head (2017) also mentions a plastic canal house that was built out of 3D printed plastic in Amsterdam in the Netherlands. The house was built by a Dutch firm identified as DUS Architect in 2014 as a way of demonstrating the potential for 3D printed architecture. The project used a big crane-like printing arm known as “Kamer maker” that can be loosely translated to “Room Builder.’

Figure 2: 3D Printed Canal House in Amsterdam

Head (2017) further highlights the use of 3D printing technology in the construction industry in the cases of a steel bridge built across a canal in Amsterdam in 2015 and the production of highly efficient dwelling structures comprising of a 3D printed pod and a combination of renewable solar and natural gas energy systems that was carried out by an architecture firm SOM in partnership with the U.S. Department of Energy’s Oak Ridge National Laboratory. Head believes that by 2020, there could be significant improvements when it comes to the use of 3D printing technology in the construction industry. She speculates that the technology

could be used in the construction of disaster shelters. She attributes this to the speed and cost-effectiveness of 3D printed buildings that could make them a good option for disaster relief when several people are in need of safe and fast shelter (Head, 2017). Head also speculates that by 2020, 3D printing technology could be used in the construction of buildings complete with systems. With the Contour Crafting system, there is hope that an entire home will be built from the ground up including electrical, plumbing, and other systems.

2.4 The Technology of 3D Printing and Its Use in the Construction Industry

Paudyal (2015) gives an insight into the technology of 3D printing; how it came about and how it has evolved over the years. He defines 3D printing as a process of formation of three-dimensional objects, components and plastic models, and other materials. This kind of technology plays a key role in the creation of tangible physical copies automatically thus reducing the number of crafts required. According to Paudyal (2015), the general principle of 3D printing usually begins with creating the object using computer software such as solid works and CAD that are followed by the printing of the same. One thing about the technology of 3D printing is that it strictly follows guidelines from the digital model created in 3D designing software. 3D systems were responsible for the development of the “Stereo Lithographic file (STL)" format although this was later used in a standard manner with the intention of imitating the original 3D model. Since its inception, 3D printing technology has undergone evolution although the transformation has come to be felt in recent years (Ma and Che, 2015). Previously, everything to do with this kind of technology was expensive including the printing equipment. As a result, only big projects could afford and use technology. This has changed in recent years with its spread, standards in place, and software

making it easier for beginners and other small projects to get access and use the technology. Paudyal (2015) proceeds to mention that a wide range of 3D printing technology types exists in the market with each of these types having unique competencies and limitations. One of the 3D printing technologies in the market is the Fused Deposition Modelling (FDM) process that appears suitable for common use given that it can perform with the filament. This is in contrast to other types and rapid prototyping processes that must use resin-based material (Poullain, Paquet, Garnier, and Furet, 2018). Paudyal takes not of the fact that more research is currently being conducted on this technology to have it used and applied more in day-to-day life.

In his study of the use of 3D printing technology, Paudyal (2015) contends that the technology involves the use of a high-power laser to fuse small nanoparticles into other end products such as metal, plastic, concrete, glass powder, or ceramic, all of which have three-dimensional desire shapes. The reputation of 3D printing is rapidly increasing in the world of manufacturing and construction thanks to the process of extrusion employed. As its framework for production, 3D printing also relies on methods such as softening or melting. Paudyal (2015) further categorizes 3D printing technology into six significant types including stereolithography (SL), selective laser sintering (SLS), selective laser melting (SLM), electron beam melting (EBM), laminated object manufacturing (LOM), and fused deposition modeling (FDM). Paudyal defines stereolithography as a 3D printing technology type or process where layers with photo reactive resin are curved using Ultraviolet (UV) laser.

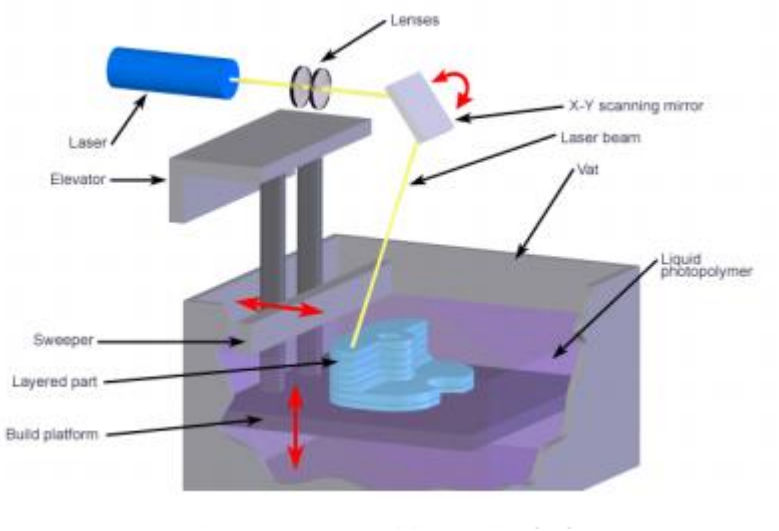

Figure 3: Stereo Lithography (Paudyal, 2015)

Paudyal (2015) explores another 3D printing technology type, selective laser sintering (SLS). He defines SLS as a process of formation of 3D product (sintered part) using laser-sinterable powder through the introduction of the powder to a machine that carries out the laser sintering process. This technique is desirable for product prototypes that require high tensile strengths or that ensure the efficiency of thermoplastic properties (Saprykin, Babakova, Ibragimov, and Dudikhin, 2015). Below is an illustration of selective laser sintering 3D technology.

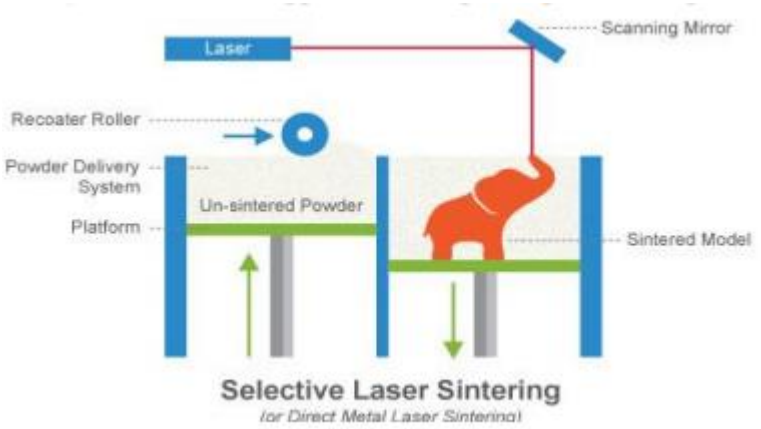

Figure 4: Selective Laser Sintering Method (Paudyal, 2015)

Another major type of 3D printing technology identified by Paudyal (2015) is selective laser melting, which is also referred to as Directed Energy Deposition. Paudyal argues that this type helps in the creation of 3D object while relying on the laser beam and metal powder. In this type of 3D printing, there is the direction of metal powder into a high-power laser beam where its deposition as a molten build material occurs. Paudyal refers to this process of deposition as laser engineered net shaping. This type of 3D printing is illustrated below.

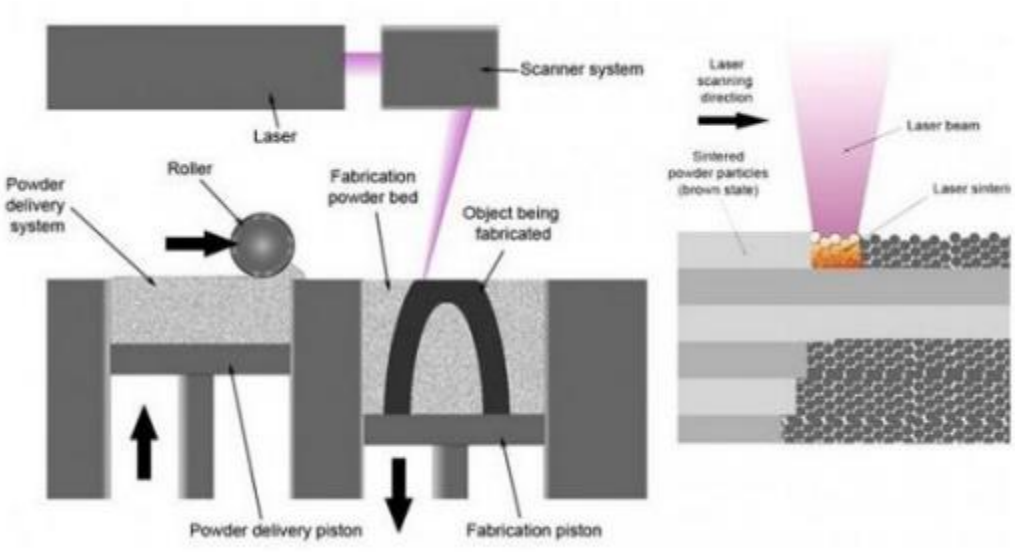

Figure 5: Selective Laser Melting Method (Paudyal, 2015)

In Electron Beam Melting (EBM), heat is used in the solidification of powders in power bed with the intention of creating 3D objects. Paudyal (2015) states that EBM occurs in various stages or passes. The first of this is where the building material is pre-heated to an optimal temperature. In the second stage, the outline of the object layer is melted and it

proceeds to the other stages where the bulk of the material in the outline made at the second stage is melted.

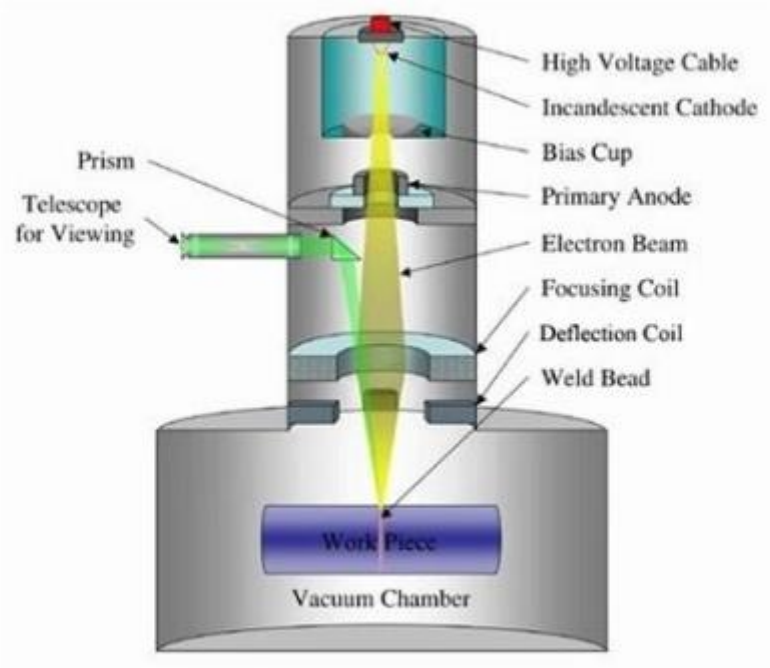

Figure 6: Electron Beam Melting (Paudyal, 2015)

Paudyal (2015) also gives a detailed overview of the laminated object manufacturing type of 3D printing. He mentions that the invention of LOM came in 1991 with a company known as Helisys playing a key role. LOM as 3D printing technology type involves the building of objects in layers whereby layer sheets of paper, metal foil, and plastic are stuck together. A characteristic of this 3D printing type is that no support structures are required since it does not work on powder-based mechanisms.

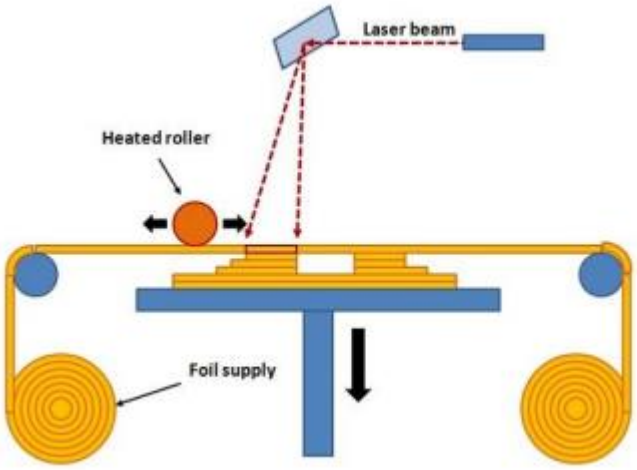

Figure 7: Laminated Object Manufacturing (Paudyal, 2015)

A common 3D printing technology type identified by Paudyal (2015) is the fused deposition modeling (FDM). He defines FDM as a rapid manufacturing process involved in the creation of new and innovative products and entails layer by layer deposition of material. There is a nozzle head from which the material is extruded and it is then deposited on a base plate where cooling occurs and the final product is removed. Some of the materials used in FDM include plastics, metals, wood, concrete, and ceramics. Below is an illustration of FDM.

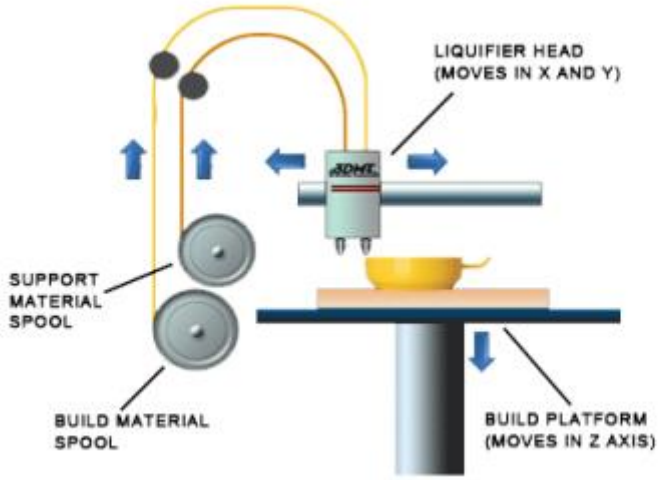

Figure 8: Fused Deposition Modeling (Paudyal, 2015)

Skold and Vidarsson (2015) argue that the terms 3D printing and additive manufacturing (AM) are usually used interchangeably since both points to the layer-by-layer creation of physical objects basing primarily on the digital files representing their design. In recent years, additive manufacturing has gradually served as a representation of the use of 3D printing in the creation of metallic components and final parts, which is distinctive from the more traditional processes used in manufacturing, construction, and other sectors. Some of the 3D printing/additive manufacturing technologies can be distinguished based on the type of bonding methods as illustrated in the figure below.

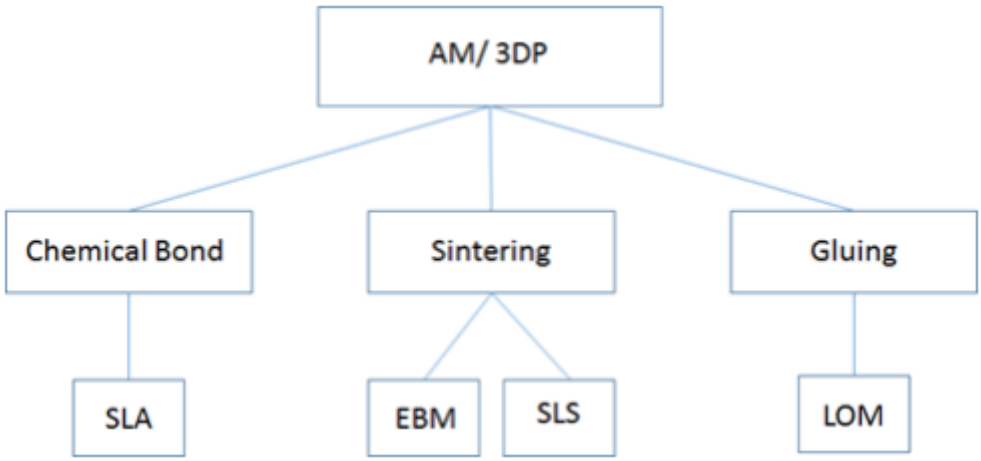

Figure 9: 3D Printing Technology Based on Bonding Method (Skold and Vidarsson, 2015)

With increased globalization in the world today, focus has been on meeting the increased human demands such as the demands for more houses. To meet this demand in the construction sector, for instance, construction companies have been forced to adopt 3D printing technologies. 3D printing has enabled construction companies to construct high-quality and highly customized houses while relying on complex geometrics in a wide range

of materials (Oberti and Plantamura, 2015). Today, 3D printing is used in construction of projects such as undercuts and internal passageways that can hardly be created using traditional models or approaches. Some of the 3D printing/AM technologies available today are stereolithography (SLA), selective laser sintering (SLS), fused deposition modeling (FDM), as well as laminated object manufacturing (LOM) (Skold and Vidarsson, 2015).

Weinstein and Nawara (2015) suppose that with the increasing population in the world today, particularly in developing countries, there is an increasing demand for housing. Unfortunately, the housing demands are not likely to be met by traditional methods of construction. This is mainly in areas or countries where higher standards of construction are required for safety purposes. Weinstein and Nawara (2015) suggest that one of the ways of addressing the housing problems faced in the world today is the use of 3D printing technology, particularly Contour Crafting (CC). The authors define Contour Crafting as an additive fabrication technology that relies on 3D printing technology and applies the same in the automation of output of concrete to build houses. A characteristic of Contour Crafting is minimal wastage as raw materials are transformed into the final product on-site (Rouhana, Aoun, Faek, Eljazzar, and Hamzeh). The construction process usually starts with computer animation where contours are built ranging from traditional styles or designs to modern designs that are more curved. The tool path is then tasked with describing aspects such as orientation, position, velocity, as well as deposition rate of the nozzle throughout construction. Subsequently, there is the conversion of the resultant information into a sequence of machine tasks that are fed into the Contour Crafting machine. Weinstein and Nawara (2015) further highlight that there is a gantry system that carries extrusion nozzles that move on two parallel tracks that are installed on-site. The system also has installed

trowels that are charged with smoothing the layer surfaces after the extrusion of concrete. Usually, the cement used does not need forms with each layer extruded keeping its form upon the addition of successive layers. There is also the possibility of automated reinforcement, and this can be achieved by adding steel mesh or fibers such as reinforced plastics. With this technology, several houses with different designs can be constructed at a go. Below is an illustration of a Contour Crafting gantry crane system.

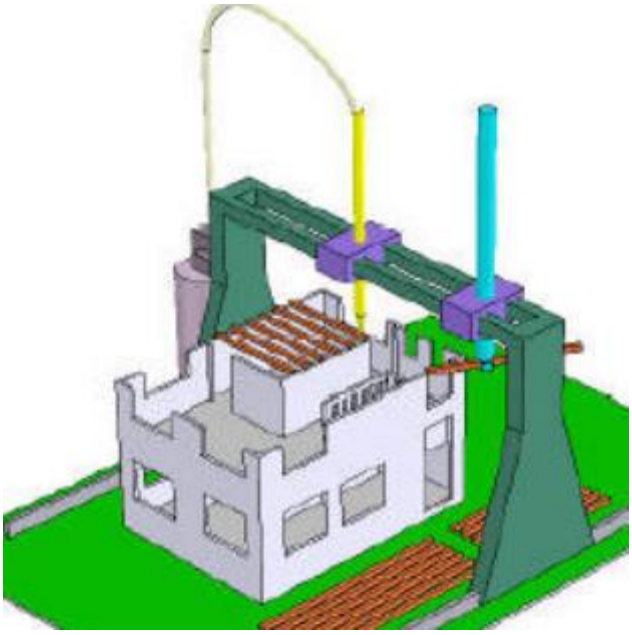

Figure 10: Contour Crafting Gantry Crane System (Weinstein and Nawara, 2015)

According to Weinstein and Nawara (2015), Contour Crafting enables the construction of a Concrete Masonry Unit (CMU) based wall with every utility conduit encompassed in the design. In this technology, there is a close correlation between the cost of construction and the time and energy the machine expends as well as the amount of materials used in the process. This technology is fast being adopted in the global construction

industry with household names such as DUS Architects based in Amsterdam and Yingchuang New Materials based in China.

According to WinSun's article "Demonstrating the Viability of 3D Printing at Construction Scale," one of the major challenges faced by the global construction sector today is the entrenchment of traditional processes that are largely unecological and unproductive. WinSun acknowledges that it is unfortunate that the construction industry despite how important it is, has hardly changed throughout history. Many of the vertical construction projects around the world are carried out by workmen who are required to add layers of building materials on top of one another. The article's argument that the traditional approaches to construction is ill-suited to modern times is based on three aspects. First, it argues that the traditional approach of using workmen has largely kept productivity low. This is highlighted by the fact that the level of productivity in the construction industry has hardly gone up over the past 50 years or so. This is unfortunate given the tremendous gains made by other industries such as the manufacturing industry. Second, the article bases its argument on the premise that today's construction industry relies heavily on the skills of individuals. However, in several countries, particularly developing countries, the individual skills tend to lack prestige and the changes in demography have reduced the size of the workforce in the sector. In developing countries, there is over-reliance on low-skilled workforce that results in compromised quality and life of buildings constructed. Third, the article's argument that traditional construction models are ill-suited for modern times is based on the premise that the traditional construction approaches result in wastes, dust, and noise. In other words, the approaches tend to defy the environmental standards of modern times. With these complexities in mind, the article suggests that the construction industry should fast embrace

the idea of 3D printing. It takes note of companies such as Yingchuang Building Technique in Shanghai, also known as WinSun, which entered into 3D printing in 2005. More than ten years later, the company has constructed a number of houses using 3D printing technology and continues to do so.

WinSun's article notes that the global construction industry stands to benefit in some ways by embracing the idea of 3D printing. With reference to WinSun's construction projects, 3D printing technology has helped in the reduction of construction times and costs significantly. The technology has also helped to increase the quality of houses constructed and ensured adherence to environmental standards. The article estimates that with 3D printing technology, the cost of constructing a standard house today is around $30,000. This is much lower as compared to the thousands of dollars spent in the construction of houses using traditional approaches. Another contribution of 3D printing technology to the construction industry, at least according to the article, is the significant increase in the speed of construction. Unlike before when standard construction methods were used, today's buildings can go up by one storey a day. The article gives an example of a 1,100 sqm mansion that can be printed in one day with the assembly taking two days. This entails the erection of internal bar structures in advance with only three workmen required in the process.

2.5 Benefits of 3D Printing Technology on Capital Cost in the Construction Industry

Perkins and Skitmore (2015) give insight into how 3D printing technology has been adopted in the construction industry thereby benefiting the sector, particularly from the perspective of capital cost. Perkins and Skitmore (2015) affirm that 3D printing in the construction industry has helped in waste reduction. In the construction industry, huge

amounts of waste are generated. It is estimated that between 3 and 7 tons of waste are usually generated when constructing a home for a single family. This is accompanied by harmful emissions generated during the process of construction. With the adoption of 3D printing, the printer produces only what is required for the construction of the final structure. Also, 3D printing integrates mechanical and electrical services in the construction process thereby resulting in the reduction of amounts of materials wasted (Pîrjan and Petrosanu, 2013). The reduction of waste translates to a significant reduction in the capital cost involved in the construction process.

Another benefit of 3D printing, according to Perkins and Skitmore (2015) is the reduction in the speed of producing final products or materials used in the construction industry. The construction of a house using 3D printing technology can only take a few hours whereas using traditional methods in the same process can take several months or even years. The reason for the increase in speed is the fact that 3D printing methods always operate at unrelenting and steady paces, which is unlike traditional models whereby workers take prolonged breaks from the production processes. The reduction in speed means that low costs are spent in terms of labor or production hence the reduction of capital cost spent in construction contexts such as in the facade of a building.

Sakin and Kiroglu (2017) argue that 3D printing technology has numerous benefits for the construction sector in particular. In the construction industry, for instance, 3D printing technology is beneficial as it is accompanied by onsite or factory applications. Another benefit of the technology is that printed products use material that needs to form them implying that fewer resources are required and less waste is generated in the process as compared to when traditional approaches are used (Sultan, Zahid, and Ahmed, 2016). Sakin

and Kiroglu (2017) also mention that in instances where 3D printing is involved, products or materials are printed on-site thus translating to a significant reduction in the cost of transportation. Also, with 3D printing, it is likely that more efficient and interesting designs will be created since the technology can come up with desirable shapes and designs that traditional techniques cannot create. In the construction industry, the reduction of labor costs is another benefit of 3D printing technology (Sakin and Kiroglu, 2017). Another benefit of 3D printing as stated by Sakin and Kiroglu (2017) are that it is accompanied with reduced costs of customized design since, with 3D printing, it costs the same when creating one item as it is to produce thousands of items. Moreover, sectors, where the technology is used witness, reduced health and safety risks. This is attributed to the fact that 3D printing is usually used in the production of assemblies that would otherwise require special equipment and necessary precautions are taken in the process (Sakin and Kiroglu, 2017). Reduced health and safety risks translate to a significant reduction in costs spent on the purchase of medicine or treatment of labor providers. Sakin and Kiroglu (2017) point to instances or cases in the construction industry where 3D printing technology has helped in the reduction of capital cost involved in the construction process. They mention the Office of the Future in Dubai where the use of 3D printing ultimately resulted in the reduction of labor costs by 50-80 percent and the reduction of the construction waste by 30-60 percent.

While examining the benefits of 3D printing technology on capital cost in the construction industry, Sakin and Kiroglu (2017) also point to the case of a Russian company that completed a 400-square-foot-home that was built from scratch in Moscow in just 24 hours. They estimate that the total cost of completing the building was a mere $10,000. This is believed to be relatively lower and more affordable as compared to habitable houses

resembling that constructed by the Russian company. According to Sakin and Kiroglu (2017), the significantly low capital cost in the construction of the home can be attributed to on-site production of materials used in the construction process thus doing away with transportation costs. Materials such as concrete mixture and other parts such a windows, fixtures, and furniture were printed on-site.

Wu, Wang, and Wang (2016) agree that 3D printing technology is beneficial, particularly to the construction industry. The authors argue that one of the major benefits of technology is that it enables mass production without interfering with customization. Every sector's primary objective is to ensure mass customization whereby products meet customers' individual orders rather than for stock. For a long time, many companies in various industries have tried to achieve the goal of mass customization, and this could be achieved with the widespread adoption of 3D printing technology. Mass production of materials required in the construction of a facade of a building, for instance, helps in the significant reduce of capital cost incurred in the process. Another benefit of 3D printing technology according to Wu, Wang, and Wang (2016) is that it has helped in the reduction of waste. This is because the process uses little and an almost exact amount of material required by the object being produced. The fact that the 3D printing process is accompanied by design flexibility is also a benefit. In this process, developers and designers come up with structures and products that can hardly be produced using traditional methods. Also, there is the idea of reduced manpower in the 3D printing process as most of the processes are automated. It is estimated that construction time is significantly reduced when 3D printing technologies are used. All these contribute greatly to the reduction in capital cost of the construction process.

2.6 Characteristics of 3D Printing Components in Building Facade of Office Building

The characteristics of components used in the construction industry such as in building a facade of an office building can be explored from the perspectives of durability, materials used, the technology involved, and usability or applicability.

2.6.1 Durability

In the construction industry, the term “durability” is defined as the ability of a building and its components to perform the required functions over time without unforeseen cost for repair or maintenance. From a personal perspective, durability refers to a component’s ability to withstand damage, wear, or pressure.

According to Paudyal (2015), a wide range of 3D printing materials can be used in construction, particularly in building the facade of an office building. However, the materials used vary depending on the 3D printing technique used. For instance, in situations where stereolithography is involved, some of the 3D printing materials used are metals that require curing, sands that do not require addition, and ceramics that require curing. A characteristic of the mentioned elements is that they are durable. As earlier mentioned, the primary objective of using 3D printing technology in construction is to have strong and durable houses, and thus, these characteristics make the mentioned materials most preferable for the 3D printing construction process. These characteristics have an impact on cost in that the cost of maintenance or replacement of materials is minimal. Also, the fact that the mentioned components are durable results in buildings that are more durable as compared to buildings constructed using traditional ways.

Paudyal argues that another 3D printing technique that can be used in the building of the façade of an office building is selective laser sintering (SLS). In this technique, some of the components or materials used include carbon fiber, nylon-filled polyamide, glass-filled polyamide, and polystyrene. A characteristic of these components is that durable; a characteristic that makes them crucial when it comes to the building of the façade of an office building. This characteristic is hardly witnessed in materials used in traditional models of building. Also, with the characteristic of durability, the resultant buildings are both strong and durable hence low cost is required on maintenance or replacement of materials or parts.

Paudyal (2015) also identifies Fused Deposition Modeling (FDM) as another technology that can be used in 3D printing the façade of an office building. In FDM, a range of materials are used including plastics, metals, woods, ceramics, and concrete. These components are known for their durability. With the durability characteristic, the components are highly prioritized when it comes to printing the façade of an office building. Their durability is in line with the overall objective of 3D printing of creating durable buildings. The durability and strength of buildings are accompanied by low operational costs in terms of maintenance and replacement of materials or parts of buildings. Also, the aspect of durability makes 3D printed houses more preferable and better as compared to those built using traditional ways.

This study will explore the maintenance and replacement concepts as they relate to durability. These concepts are mentioned in the above review of literature on durability and its impact on cost in building a façade of an office building.

2.6.2 Usability

The term “usability” is part of the broader term “user experience” and refers to the ease of access and use of a particular product or component. In the context of 3D printing components in the construction industry, it refers to the ease of use of these components in the construction process.

According to Thomas and Gilbert (2014), 3D printing, also known as additive manufacturing, plays a key role in the construction sector. 3D printing has gradually been adopted in building homes and offices including the façade of office buildings. Thomas and Gilbert (2014) proceed to mention that 3D printing components used in the construction industry, particularly in building the facade of office buildings, include polymers and polymer blends, composites, metals, graded or hybrid metals, ceramics, investment casting patterns, sand molds and cores, as well as paper. Other than their durability, these components are known for their usability in 3D printing process in construction projects (Rael and San Fratello, 2011). These components are easy to use during the construction process, which is hardly witnessed in the case of components used in traditional building models. As a result of usability, the costs required for operation in terms of maintenance and replacements are lower as compared to operational costs required for buildings erected using traditional models.

This study will explore the maintenance, replacement, labor, and production concepts as they relate to usability. These concepts are mentioned in the above review of literature.

2.6.3 Applicability

The term “applicability” can be defined as how useful or appropriate something is for a particular task. In the context of 3D printing components, their applicability points to how useful or appropriate for the construction of a façade of an office building.

Canas (2014) also investigates the characteristics of 3D printing components used in the construction industry. He notes that unlike before, today’s 3D printers have allowed companies in the construction sector to print high-quality components that are applicable or appropriate when it comes to construction. According to Canas (2014), one of the materials that can be used in the construction industry to build the façade of office buildings is plastics with either nylon or polyamide being used frequently. Both nylon and polyamide are used in the construction sector as well because of their applicability. At times, applicability is ensured when the two plastics are combined with Aluminum thus producing a material known as Alumide. Other plastics that can be used with 3D printing are ABS and PLA plastics although these are not consistent with 3D printing because of the lack of durability or flexibility. The applicability translates to low costs, particularly during operation, making 3D printing more preferable in the construction industry as compared to traditional models.

This study will explore the low costs of operation associated with the applicability of 3D printing components in building a façade of an office building. The concept of low operation is mentioned in the above review of literature.

2.6.4 Maintainability

The term “maintainability” refers to the probability of performing a successful repair or maintenance action for a particular component within a given time. From a personal perspective, it is all about the ease and speed with which a given component can be kept at

operational status. Maintainability is a typical characteristic of 3D printing components used in the construction of a façade of an office building.

Canas (2014) identifies metals as the most commonly used material in 3D printing in the construction industry. Some of the commonly used metals in 3D printing processes are aluminum, cobalt derivatives, and stainless steel. In recent years, gold and silver have been added to the metals that can be used in 3D printing processes. Another metal that has been added is titanium, which is known to be one of the strongest metals. These metals are preferred as 3D printing components mainly because of their maintainability. In addition to the mentioned metals, Canas (2014) lists ceramics among the materials used in 3D printing in the construction industry. The only difference between ceramics and other materials used in 3D printing is that after printing, they must go through the same process as other ceramic parts produced using traditional methods would. The characteristic of maintainability translates ease and fast speeds of operation thus reducing costs.

This study will explore the concepts of ease and fast speed during operation as they relate to maintainability. These concepts are mentioned in the above review of literature.

2.7 Capital Cost of 3D Printing

Capital cost is the cost associated with the procurement of 3D components, transportation to site, construction, and installation. In the article "Cost and Effectiveness of Additive Manufacturing: A Literature Review and Discussion," Thomas and Gilbert (2014) argue that capital cost in the construction industry involves "well-structured" costs such as labor, material, and machine costs as well as "ill-structured" costs associated with machine setup, build failure, and inventory. Thomas and Gilbert (2014) state that capital cost

effectiveness in the construction industry can be examined from the aspects of overproduction, transportation, rework or defects, over-processing, motion, inventory, and waiting.

According to Thomas and Gilbert (2014), 3D printing technology has played a key role in the reduction of capital cost spent in the areas of inventory and transportation. Concerning inventory, 3D printing has allowed the production of various materials used in the construction industry primarily on demand. Thomas and Gilbert give the statistics that in 2011 alone, there were $537 billion in inventories in the manufacturing industry, which represented 10 percent of the revenues that year. Apparently, the resources that were spent in the storage and production of products could have been used in other important areas if there was reduction in inventory. Traditionally, in the construction industry, materials are ordered rapidly and they end up becoming idle. Of course, any machinery, equipment, or material waiting is usually costly. Thus, traditional models in the construction industry make it costly and require too much time to produce materials on demand (Thomas and Gilbert, 2014). The outcome is a huge amount of inventory of infrequently ordered parts or materials. When it comes to transportation, 3D printing in the construction industry has made it possible to produce materials simultaneously on-site making it easier to complete an entire construction project. On the other hand, traditional approaches in the construction industry entail the production of materials or parts in several or different locations with an inventory for each being stored. When needed, the materials are then transported to the construction site and are later assembled into a final product as can be seen in the figure below.

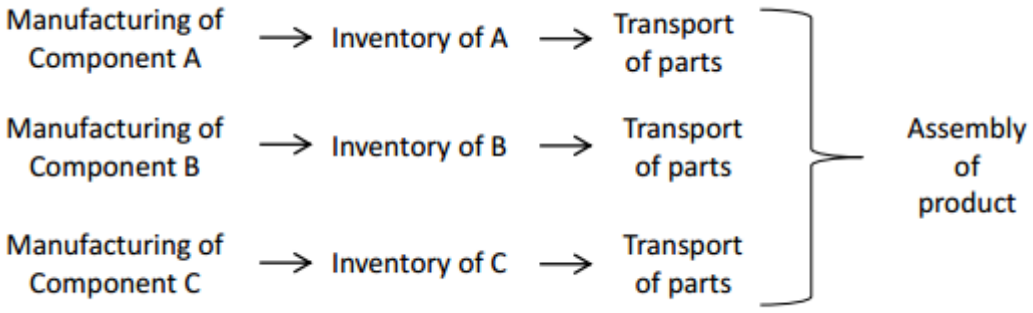

Figure 11: Traditional Manufacturing Flow (Thomas and Gilbert, 2014)

Thus, 3D printing has the capability of reducing the capital cost incurred in the transportation of materials in the construction sector as it replaces some of the steps above for some materials used in the sector. As a result, 3D printing might allow for the completion or construction of an entire project with minimal interference (Thomas and Gilbert, 2014).

Thomas and Gilbert (2014) further examine the capital cost advantage of 3D printing technology as it relates to the construction industry in terms of supply chain management. Thomas and Gilbert's article argues that the supply chain in the construction industry entails the purchasing, operating, distribution, and integrating of building materials or products. In purchase, the focus is on sourcing the suppliers or various products or materials required such as polymers and polymer bends, composites, metals, graded or hybrid metals, ceramics, investment casting patterns, sand molds and cores, as well as paper (Janssen, Blankers, Moolenburgh, and Posthumus, 2014). In operations, the focus is on perspectives such as demand planning, forecasting, and inventory. Distribution entails how goods or products move from one point to another. Integration in itself is about creating a supply chain that is sufficient (Thomas and Gilbert, 2014). 3D printing could have significant impacts in the construction industry's supply chain management as it is likely to reduce the need for the

purchasing, operations, and distribution of materials within the industry.3D printing technology can bring the producers or various construction materials such as those already mentioned closer to construction companies or sites thus reducing the links in the supply chain. By cutting the links involved in the construction industry's supply chain, 3D printing helps to reduce the capital cost involved. However, the traditional way of construction still involves the purchase of building materials from suppliers and distributing or transporting them to the sites of construction. The long supply chain management involved in the traditional models of construction increases the capital cost in the entire construction process. Based on this, the 3D printing technology tends to be cheaper than the tradition way of construction.

Thomas and Gilbert (2014) add that 3D printing technology in the construction industry helps to reduce the number of links in the supply chain and bring production closer to construction projects. This results in a reduction in vulnerability and disruptions involved in the construction process. In the construction industry like other industries, disasters or disruptions stop or hinder the production and delivery of building materials and products thereby raising the capital cost. However, with 3D printing technology, production of building materials is brought closer to construction sites. This results in a more decentralized production whereby several 3D printers are required to produce a few products. This is different from the traditional way where production of materials happens far from the construction sit and few facilities produce many products required for the construction process (Thomas and Gilbert, 2014). In the traditional way of construction, material resource providers deliver to the manufacturers of parts and components, who might deliver parts and components to one another then to assembly plants (Thomas and Gilbert, 2014). From the

assembly plants, the assembled building products are delivered to retailers or distributors. Thus, in the traditional way of construction, there are high chances of disruption of deliveries to construction sites thereby raising the capital cost (Thomas and Gilbert, 2014).

The article “Demonstrating the Viability of 3D Printing at Construction Scale” gives an example of how Winsun’s 3D printing technology in the construction industry has helped to reduce the capital cost incurred in the sector. It gives insight into one of the buildings in Dubai known as the “Dubai Future Foundation” that was printed in Suzhou but constructed in Dubai. The assembling of the project took only a few weeks. The article argues that as compared to traditional on-site construction, Winsun’s 3D printing technology has helped the company to save about 80 percent on capital costs. It is believed that 3D printing helped to save about 60 percent on labor costs and 60 percent on potential wastage.

The capital cost of 3D printing can also be based on the characteristics of 3D printed components of durability, usability, applicability, and maintainability.

2.7.1 Durability:

The primary objective of using 3D printing technology in construction is to have strong and durable houses, and thus, this characteristic makes 3D printed materials most preferable for the construction process. Durability has an impact on capital cost since durable houses require minimal labor.

2.7.2 Usability:

3D printed components are easy to use during the construction process, which is hardly witnessed in the case of components used in traditional building models. As a result of

usability, the capital costs required, especially in terms of labor and production, are lower as compared to capital costs required for buildings erected using traditional models.

2.7.3 Applicability:

3D printed components such as nylon and polyamide are used in the construction sector because of their applicability. At times, applicability is ensured when the two plastics are combined with Aluminum thus producing a material known as Alumide. The applicability translates to low capital costs, particularly in terms of labor and production, making 3D printing more preferable in the construction industry as compared to traditional models.

2.7.4 Maintainability:

Metals are the most commonly used 3D printed components the construction industry because of their maintainability, which is the ease and speed with which they can be maintained or restored to operational status. Some of the commonly used 3D printed metals are aluminum, cobalt derivatives, and stainless steel. The characteristic of maintainability translates to ease and fast speeds during the construction process thus reducing the capital cost.

2.8 Operational Cost of 3D Printing

Operational costs are the costs that are required for the day-to-day functioning and maintenance of a construction project. They include general and administrative costs as well as maintenance, replacement, and repair costs. In the article “Cost and Effectiveness of Additive Manufacturing: A Literature Review and Discussion,” Thomas and Gilbert (2014) argue that operational cost in the construction industry entails the maintenance and replacement of building components. In examining the operational costs of 3D printing, it is

important to compare 3D printing to other traditional processes used in the construction industry. This makes it easier to determine how cost-effective 3D printing or traditional models are, particularly in the construction industry.

Thomas and Gilbert (2014) argue that the operational cost of 3D printing in the construction industry is higher than that incurred in traditional construction practices. These can be examined from the perspective of the materials or components used in 3D printing construction that will need to be maintained or replaced during the process of construction. Thomas and Gilbert (2014) presume that the cost of maintaining 3D printed components used in the construction sector is very high. For instance, some of the materials used in 3D printing in the construction industry are metal and plastic that will require careful maintenance and operation upon the completion of the project. Thomas and Gilbert (2014) argues that metal parts or materials made from aluminum alloys are sold at €2.59 per part for traditional manufacturing and €25.81 per part for 3D printing using the selective laser sintering technique. It can be seen that in the long run, the operation cost for 3D printing will be nearly ten times higher and more expensive than that of traditional construction. Moreover, higher operational costs for 3D printing are evident in the maintenance and replacement of 3D printed plastic materials or components. Thomas and Gilbert (2014) compare the costs involved in purchasing plastic components produced using 3D printing technology of selective laser sintering. In this case, the major costs are the machine cost per part that falls between 58.7 and 65.9 percent of the total cost and the material cost that is between 29.1 percent and 30.4 percent of the total cost. In other words, the costs involved in the production of 3D printed components are higher than those involved in the production of components used in traditional models of building. This translates to increased operational costs in the

maintenance and replacement of 3D printed components during construction (Thomas and Gilbert, 2014).

Thomas and Gilbert (2014) proceed to mention that operational cost in 3D printing includes the machine cost. There is no doubt that machine cost is one of the most significant costs that are involved in 3D printing. According to Thomas and Gilbert (2014), the machine cost in 3D printing was $73, 220 in the United States. There has been a fluctuation in machine costs with lower costs being recorded in 2010. Although the machines costs involved in 3D printing could be decreasing, they remain higher than machine costs in traditional construction practices.

Thomas and Gilbert (2014) also argue that there are product enhancements and quality in 3D orienting technology that translate to high operational costs involved in maintenance and replacement of components. Although 3D printing in the construction industry comes with more geometric freedom and creates more flexibility, designs require support structures that raise operational costs in the long run. This is contrary to the traditional ways of building where there are simple designs that do not require support structures translating to low operational cost in maintenance and replacement of components. Somehow this is not in keeping of 3d printing with the benefits that were cited in the Benefits of 3D Printing Technology on Capital Cost in the Construction Industry section, this would be investigated to check whether anomaly is correct.

CHAPTER 3- METHODOLOGY

3.1 Introduction

The way in which a study is conducted is mainly dependent on the research philosophy that the researchers subscribe to, the research strategy used, as well as the research instruments used in pursuit of a specific goal, which in this context points to the research objectives. This chapter is all about the methodology that will be used in the research. It entails the research philosophy, the research strategy, research design, data collection, interview protocols, and data analysis.

3.2 Research Philosophy

Research philosophy refers to the belief about how data about a phenomenon should be collected, analyzed, and utilized. It is the principal belief system that guides research to be undertaken and covers the choice of method to be used for the study. There are three major aspects of research philosophy including epistemology, ontology, and axiology. Epistemology is a common concept, particularly in the field of study and research. Scotland (2012) argues that epistemology is concerned with what can be considered acceptable knowledge in the field of study. In other words, it points to what is known to be true, and as such, it opposes the term doxology that refers to what is believed to be true. The concept of ontology is majorly concerned with social beings (Scotland, 2012). Its primary focus is on the nature of reality and entails the aspects of subjectivism and objectivism. The third important aspect of research philosophy, axiology, is one of the branches of philosophy and is concerned with studying judgements about value. Research philosophies are further categorized into positivism, interpretivism, realism, as well as pragmatism.

Positivism is also known as scientific philosophy, and it is based on the belief that reality is always stable and can only be described and viewed in an objective manner. Kaboub (2008) believes that this philosophy opines that reality can be manipulated through varying an independent variable with the aim of identifying existing relationships between real world elements. It is on the basis of these interrelationships that predictions can then be made. Over the years, the positivist paradigm has been associated with natural sciences. This has sparked debates on whether the paradigm is suitable when it comes to social science research. With this paradigm, the researchers have the obligation of maintaining data independence alongside an objective point of view. Moreover, one of the things emphasized in this paradigm is replication, which is believed to be the best way of testing the validity of knowledge as the review of the same results by different observers or participants should come to similar findings or outcomes.

The interpretivism paradigm maintains that to fully understand reality, there must be subjective interpretation of as well as interpretation of reality. It also highlights the ability of the individuals taking part in the research to affect the phenomenon being studied (Thanh and Thanh, 2015). This paradigm points to the belief that reality is not only multiple but also relative. It further contends that during research, both the researcher and informants must remain interdependent and interact to be able to understand and interpret the various behaviors exhibited by humans rather than focusing on the generalization and prediction of the causes and effects of the exhibited human behavior.

The realist paradigm, in the context of research, is grounded on the argument that most objects exist independently of the researchers' knowledge. This points to the existence of a reality that is independent of the mind of humans (Sobh and Perry, 2006). The final

paradigm, pragmatism, points to the possibility of working with both the interpretivist and positivist and that the most important factor that determines the research philosophy is the research question. The pragmatist paradigm tends to be more concerned and focused on the aspects of usefulness and utility rather than abstract notion of truth. This is attributed to the fact that the value of knowledge usually underlies practical usefulness as well as the capability of resulting in informed change. Pragmatists also argue that the knowledge, in most cases, is created and ultimately used for action.

Based on the paradigms explored above, this study will adopt the positivist paradigm. This is similar to the study by Skold & Vidarsson (2015) that analyses the potentials of 3D printing in the construction industry. The argument about the adoption of this paradigm is mainly because the research will rely on the actual data collected without integrating bias to get the truth and facts on the impact of 3D printing on the capital cost of a façade of an office building. The positivist paradigm is known for its alignment of knowledge generation in a systematic manner with the intention of enhancing precision when it comes to describing various parameters as well as establishing the existing relationship between the parameters. The positivist approach is the most appropriate for this study given its emphasis on an objective approach. Through this, the study prioritized research methods that are mainly qualitative. This research adopted a qualitative approach that entailed the collection of data, development of analytical framework, and analysis of the qualitative data collected. The aim of this study is to examine the pattern that exists between the research theory using interviews as an instrument for data collection.

3.3 Research Strategy

A large number of research strategies has been identified by research experts. This study relied on one key research strategy, which was interviews. According to Mathiyazhagan and Nandan (2010), interviews allows the research team to collect data or information about various practices, participants' views or situations at a given point in time through the use of questions that are answered by participants or respondents. Once the data is collected using the method mentioned, the researchers resort to analysis of data with the aim of drawing inference from the data regarding existing relationships between variables. A strength of using interviews is that the researcher can study multiple variables at a time, which can hardly be achieved in field or laboratory experiments. However, this strategy cannot determine the insights related to the causes of or process that involved in the phenomenon being measured. Another weakness is the possibility of bias witnessed in the case of self-selecting nature of respondents as well as the researcher's design of the interviews (Mathiyazhagan and Nandan, 2010). Based on the objectives of this research, the research team sought to investigate or determine how 3D printing components impact the capital cost of a façade of an office building. In order to conduct the research, interviews were developed to get participant's views or opinions on the same. The interviews were administered to participants for the better part of the study, and they were crucial data collection devices.

3.4 Research Design

Research design can be defined as the researcher's plan for the selection of various sources as well as type of information that helps to answer the research question (Labaree,

2009). In most cases, the research design is a framework that helps researchers to specify various relationships between variables as well as give an outline for every procedure undertaken from the hypotheses to the point of data analysis. Many researchers use either quantitative or qualitative research design although mixed research techniques where both the quantitative and qualitive designs are combined can also be used. The mixed research design is preferred at times as it takes advantage of the strengths of both the quantitative and qualitative research designs (Labaree, 2009). Qualitative research is usually concerned with the attributes, characteristics, and features of a phenomenon that can be thematically interpreted. For this study that sought to determine the impact of 3D printing components on the capital cost of a façade of an office building, the researcher selected the qualitative research design.

The research design can also be defined from the basic reporting research to the more advanced predictive research. Between the basic reporting research and the more advanced predictive research lies a number of research designs including exploratory, experimental, descriptive, observational, and causal-explanatory. For the purposes of this study, the descriptive design was used in which the concern was understanding how 3D printing components impact the capital cost of the façade of an office building. In other words, the focus was on how 3D printing components produce change in the capital cost of a façade of an office building.

3.4.1 Population and Sample Size

For this study, the targeted population was professionals in the construction industry who are conversant with and use 3D printing technology. Some of the targeted professionals

included project managers, architects, and engineers. Since this was a qualitative research, a small sample size was required. Authors and research experts argue that qualitative research or analysis requires a smaller sample size as compared to quantitative research or analysis. Sample size can be defined as the number of individual samples measured or observations that are used in a study. For this study, a sample of 10 participants were recruited and out of this, 1 participant was a project manager, 4 were architects, 4 were engineers, and one was a head of 4IR. In this study, the 3D printing components used in building that were explored included metals, ceramics, carbon fiber, nylon-filled polyamide, glass-filled polyamide, polystyrene, concrete, wood, and others. Their impact on the capital cost of a façade of an office building was inferred from the expenses involved in the purchase of equipment, operation, and maintenance of a façade.

3.4.2 Interviews

Interview was the major research tool or instrument used in this study. Interview as a research tool is usually used in cases where the collection of qualitative data is probable. Interviews have an upper hand over other research tools such as the questionnaire as they allow the researcher an opportunity to collect extensive and in-depth data. The collection of data is through interviews with predetermined individuals with knowledge and good insight in the research area or field. Since this study required the collection of qualitative data, interviews were conducted to have an insight of what the application of 3D printing is in the construction process and how this impacts the capital cost, particularly in the construction of a façade of an office building. The interviews were conducted with 10 participants working

in different fields in the construction industry to get a wide picture of the impact of 3D printing in the construction sector.

With the researchers' intention of ensuring that the interviewees were guided in the right direction, semi-structured interviews were chosen and issued as the most effective or appropriate interview structure. In the case of semi-structured interviews, the researcher predefines questions and combines them with elaborations and explanations around a specific subject. Another advantage of using semi-structure interviews that prompted their use in this study is that less training regarding the interview technique is required (Segal, Coolidge, O'Riley, and Heinz, 2006). This is because the interview has a set of specific questions that he or she can choose from. The benefit of semi-structured interviews for this study was that the researchers hardly had any training on interview techniques. Another benefit of semi-structured interviews for this study was the ability to discover matters that are unknown, which was suitable for this study given the unexplored scope. There was the belief that the use of semi-structured interviews could help to raise questions and problems that have not been perceived or considered as problems before. The use of semi-structured interviews for this study also allowed for a comparison of different interviews and this was of importance to this study given that it was qualitative-oriented (Segal, Coolidge, O'Riley, and Heinz, 2006). Moreover, with inclination to the qualitative approach, the data collection focused on fewer interviews with fewer participants.

The different interviews were conducted with various professionals or experts in the construction industry. The interviews were also held with people with an understanding or knowledge of 3D printing technology. The basis for the interviews was the collection of data about what or how 3D printing components impact the capital cost of a façade of an office

building. The overall intention was to get information on how 3D printing components either increase or reduce capital cost of a façade of an office building.

3.5 Data Collection

For this study as described in the previous sections, interviews are selected as an instrument for collecting data. To do so the following data collection protocols are described.

3.5.1 Ethics Used at Research

To facilitate our note-taking, we are going to tape record our conversations with you today. We will request you to sign the release form. We would like to clarify that only researchers involved in the project will be pricy to the recordings that will ultimately be destroyed after transcription. Respondents or participants are also advised to sign a form that meets human subject requirements during research. The document states that: (1) confidentiality of every information provided will be maintained, (2) your participation in this research is voluntary and that you are free to stop at any time in case you feel uncomfortable, and (3) the research team does not intend to inflict any harm. Your agreed participation in this research is appreciated. This interview will last no longer than one hour. Throughout the time, several questions relating to your opinion on how 3D printing components impact the capital cost and operational cost of a façade of an office building will be asked.

3.5.2 Interview Protocol Design

The interview protocol is composed of two main concepts, the capital cost and operational cost. The capital cost is composed of three themes, of which are durability, usability and applicability, and maintainability. While the operational cost includes two themes, of which are replacement and maintenance. The below sample is an interview protocol design that will be utilized for all of the themes. Collected data is included in the appendix section.

Theme:

Title:

Experience:

Position:

Date:

Location:

Interviewer:

Interviewee:

Q1:

Probes (if used, depending on how structured the interview)

Answer:

Reflective:

Q2:

Probes (if used, depending on how structured the interview)

Answer:

Reflective:

Q3:

Probes (if used, depending on how structured the interview)

Answer:

Reflective:

3.6 Data Analysis of The Methodology

The data collected from the interviews were of qualitative nature hence there was a need for translating and understanding the data. The grounded theory method was chosen for the purposes of translating and understanding the collected data. With the grounded theory method, researchers can come up with a model that can later play a key role in the explanation of a phenomenon. The grounded theory method also allows researchers to analyze specific cases in a study and use the conclusions made from the cases in a general manner. A number of steps are performed when it comes to conducting a grounded theory for the purposes of analyzing data collected in research. First, the researchers ought to write short memos as they get acquainted with the data or information collected from various past studies and literature. Second, the raw data collected from respondents should be coded, and this can be achieved through the use of various variables such as names. Coding the data collected in this study can use the names such as interviewee 1, interviewee 2, interviewee 3, interviewee 4, interviewee 5, up to the last interviewee. Third, the researchers focus should then be on categorizing the codes by finding links existing between different codes and grouping the codes together. After the categorization of the codes, researchers are charged with reducing the number of categories as well as reducing the number of codes that could not be grouped. This would be essential since a huge number of categories could likely be problematic for the researchers. To achieve this, it is advisable for the researchers to group the categories with strong connections into a single big category while grouping those with weaker connection into a category with a wider scope. This should be a continuous cycle for the researchers in their analysis of collected data.

CHAPTER 4- DATA ANALYSIS

4.1 Introduction

The purpose of this thesis is to investigate the impact of 3D printing components on the capital cost of a façade of an office building. Thus, the analysis chapter is going to focus on data collected during research and will be based on two major prospects. One of the prospects analyzed is the impact of 3D printing components on capital cost. Under this, the focus will be on how various characteristics of 3D components such as durability, usability and applicability, as well as maintainability impact capital cost. The second prospect analyzed is the impact of 3D printing components on operational cost. Under this, the focus will be on how aspects or characteristics of 3D printing components such as replacement and maintenance impact operational cost.

4.2 The Impact of 3D Printing Components on Capital Cost

The first step is to determine the most significant characteristics of 3D printing components that impact the capital cost of a façade of an office building. As explored in the Literature Review chapter, the characteristics of 3D printing components can be explored from the perspectives of durability, usability and applicability, as well as maintainability.

4.2.1 Durability

As can be read in the Literature Review chapter, durability is one of the most significant characteristics of 3D printing components. In the construction context, the term “durability” is defined as the ability of a building and its components to perform the required functions over time without unforeseen costs. It can also be defined as a component’s ability to withstand damage, wear, or pressure. During the study, various aspects of durability and

how they impact the capital cost were explored. The below chart is a demonstration of the concepts being explored through interviews.

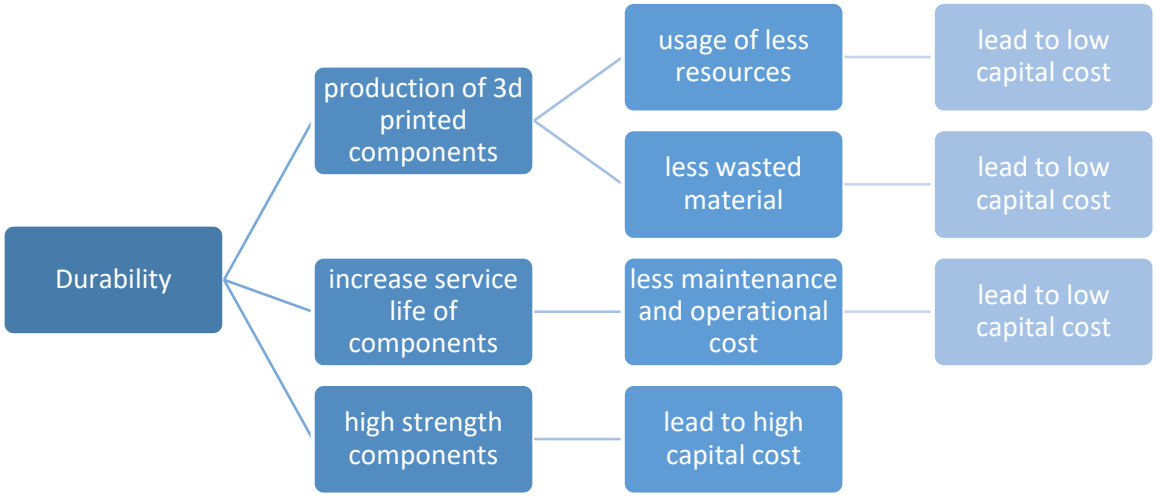

Figure 12: Durability Concepts Being Explored Through Interviews (By the Author)

The findings of how the above aspects of durability impact capital cost are presented in the table below.

Table 1: Interviewees' Responses on Durability Concepts

Interviewees	Response to Q1	Response to Q2	Response to Q3	Response to Q4	Response to Q5
1	Durability will increase capital cost of the building construction in quality and time.	No, it requires more resources that depends in design and material, less resources in man power.	Yes, depending on the design or component being printed.	Yes, it will increase the cost that we should use more durable materials.	Yes, because more material and time will be consumed.
2	3D printing process makes the creation of parts product cheaper and more accessible.	Yes, highly sustainability and efficiency in production through using the least amount of material and energy in production.	Yes, as this a relatively new technology that is gaining momentum the material cost can still remain high. However, the range of materials is growing and this makes it	No, it doesn't influence the capital cost because more service life of the components less capital we need.	No, when business has the ability to confirm a design before committing it to production, it can be help to remove the risk of errors, wasted materials and money.

			possible for the price to decrease over time.		
3	3d printed components are durable, strong, and useful. And this influences the capital cost by reducing the material usage.	Yes, it does, especially when it comes to labor and usage of equipment.	Yes of course it does, less usage of material means less waste, and that will save money to buy new material when needed.	I believe it will affect on the long term, when it comes to maintain and replacing the parts the cost will be lower.	I think it depends if there is a wide range competition, but also, I think it may higher the capital cost.
4	3D printed components are considered as durable solution for building facades with lower capital cost.	3d printed components require less resource but high qualification.	It can reduce the waste cost of pre-form components and pre-construction procedures workflow material as it will be direct printed to the required shapes.	It will reduce the capital cost as increasing the quality of the product will make it work for long life time.	If we use a high strong durable 3d component will increase the capital cost
5	The 3d printed components durability influence capital cost. It makes it lower.	Yes, it requires less manpower, save the transportation of materials, labors, etc.	Yes, in 3D printing has no waste of material, therefore, it will reduce the cost of waste management in the site.	The 3D printing decreases the capital cost, since it decreases the cost of maintenance.	No, it will make the building/ product stronger and it will increase the lifetime
6	The initial cost of 3d printing will increase the cost, but from other aspects of labor, material, and reduction of human faults it will be lower in cost.	Yes of course, reduction of factory production	More accuracy in calculation of required material, which will reduce cost and waste, and assumptions of any calculations	Depend on the treatment used to improve the material quality; if it's expensive it will increase the cost.	Durable strong 3d component lead to high cost.
7	If the quality is increased, that means by default the capital cost will increase, and it make capital cost more expensive.	High quality printed components can increase the capital cost, but for the long term it will decrease the maintenance cost.	Yes, the 3d require less resource, since you are controlling the amount of material that is needed, through the printing process.	Yes, if the service life of a 3D components can last longer, that mean by default the price will be increased.	Yes, it all depends on the supply and demand. But, basically better-quality lead to high capital cost.
8	Durability of 3D printed components requires low maintenance and labor hence low capital cost.	As it is mostly automated, resources are relatively less particularly at post setup stage.	Material and waste management are correlated, the less material the less waste and obviously less cost of disposal.	The more durable, the more service life the less maintenance, as a result less capital cost to maintain the said components.	Initial cost might be higher in relation to sustaining/maintaining the components in future.
9	3d components are designed and produced to be more durable than normal building components which may influence the cost, but its long service life and high-quality results	Produced components are precise and proper with less material consumed.	Yes, o certain extent, reduced wastes have influence, as long as the material is the major factor of the cost; and whereas bringing such technology	In my view, service life has nothing to do with the up-front, however it influences the life cycle cost.	Either Yes or No is correct; depending on the cost of the procedures been used to produce/execute/manufacture this component, whether it is negligible or not.

	in reducing the maintenance cost		into a site is negligible.		
10	3D printing component durability makes capital cost higher although this will reduce in the future.	Depending on the use. Generally, a professional would use it in the most effective way.	Depending on the way the material is being utilized.	No, not on the capital cost since the material being used is the same whether 3D printed or not.	No, it shouldn't, as the material will be the same whether 3D printed or not. The difference is in the constructability and pre-setup

4.2.1.1 Production of 3d printed components

Most of the participants agreed that durability of 3D printing components reduces the capital cost in a façade of an office building. A majority of the interviewees agreed that in the production of 3D printed components, there is usage of less resources and less wasted material.

Interviewee 2 agreed stating that:

> "*highly sustainability and efficiency in production through using the least amount of material and energy in production*" -Project manager.
>
> Interviewee 3 agreed stating that:
>
> "*Yes, it does, especially when it comes to labor and usage of equipment*"- Senior Engineer

Interviewee 5 also agreed arguing that:

> "*Yes, it requires less manpower, save the transportation of materials, labors, etc.*" - Principal Architect.

However, 2 interviewees disagreed and stated that production requires more resources and material. Out of the two, one argued that production requires less manpower.

Interviewee 1 stated that:

"*It requires more resources that depends in design and material, less resources in man power*" -Architect Engineer.

Interviewee 7 stated that:

"*High quality printed components can increase the capital cost, but for the long term it will decrease the maintenance cost*"- Senior Researcher

The interview data reveals that 3D printed components require less use of resources in production. This confirms the finding of Thomas and Gilbert (2014) that the production of components through 3D printer is much easier and requires fewer workforces, material, and waste as compared to the traditional mode. The technology of the machine is designed to print a component through a layering process that produces durable components with an efficient amount of material being used printed into any shape desired (Thomas and Gilbert, 2014). Thus, this is correlated to the waste management; the less material being utilized the lower the waste and the cost. This is confirmed by Interviewee 8:

"*Material and waste management are correlated, the less material the less waste and obviously less cost of disposal*."- Area Manager.

Evidently, the less usage of resources and less wasted material in production of 3D printed components lead to low capital cost.

4.2.1.2 Increasing Service Life Of 3D Printed Components

As can be seen in the table above, several interviewees stated that increasing the service life of components means less maintenance and capital cost. The majority agreed that increasing the service life of the components will decrease the capital cost as less maintenance is required as a result.

Interviewee 2 stated that:

> "*It doesn't influence the capital cost because more service life of the components less capital we need*" – Project Manager.

Interviewee 3 stated that:

> "*I believe it will affect the capital cost on the long term, when it comes to maintain and replacing the parts the cost will be lower*"-Senior Engineer.

Interviewee 4 affirmed that:

> "*It will reduce the capital cost as increasing the quality of the product will make it work for long life time*"- Principal Architect

However, a few interviewees were in disagreement arguing that increasing the service life of 3D printed components increases the capital cost.

Interviewee 1 stated that:

> "*It will increase the cost that we should use more durable materials*"-Project Manager

Interviewee 6 said that:

> "*It depends on the treatment used to improve the material quality; if it's expensive it will increase the cost*"-Architect.

The interview results reveal that producing very high durable materials may increase the cost in the short term but it will benefit a reduction of the maintenance and replacement cost that will impact the overall capital cost to be lower. According to Thomas and Gilbert (2014), this is achieved through the ease of production of the components since it is a "build through order" process that is designed through a software and being printed immediately on site. This eases the replacement and maintenance of the parts away from the complexity of

creating casting molds or assembly aspects. Based on that time is saved, long run cost is maintained, and material is utilized efficiently as claimed by interviewee 3 claimed:

> "*I believe it will affect on the long term, when it comes to maintain and replacing the parts the cost will be lower*." – Senior Engineer.

Arguably, an increase in the service life of 3D printed components causes a decrease in the maintenance and operational costs that leads to low capital cost in the long run.

4.2.1.3 Producing High-Strength Components

A majority of the interviewees stated that producing high-strength 3D components results in high capital cost. The majority of them agreed that production of high-quality components leads to a higher cost yet each shared a different explanation. 3 of 7 stated that production of strong materials leads to higher cost, 2 of them explained that it depends on the supply demand, manufacturing, and availability of the components, while the other 2 affirmed based on different experiences, one of them claimed that if it was for a competition then the price is higher, while the other stated that the cost of sustaining them would be higher on the long term.

Interviewee 1 stated:

> "*Yes, because more material and time will be consumed*"-Project Manager.

Interviewee 3 said:

> "*I think it depends if there is a wide range competition, but also, I think it may higher the capital cost*"- Senior Engineer.

Interviewee 4 stated that:

"*If we use a high strong durable 3d component will increase the capital cost*"- Principal Architect.

Interviewee 6 affirmed that:

"*Durable strong 3d component lead to high cost*"- Architect

However, a few interviewees rejected the argument that producing very durable strong 3D components leads to high capital cost. Interviewee 2 affirmed that the ease of production with lower resources usage saves the cost, interviewee 5 confirmed that stronger materials increase their service life and lowers operational costs, while interviewee 10 stated that since the construction cost will only differ this won't alter the capital cost.

Interviewee 2 said that:

"*When business has the ability to confirm a design before committing it to production, it can be help to remove the risk of errors, wasted materials and money*"-Project Manager.

Interviewee 10 stated that:

"*It shouldn't, as the material will be the same whether 3D printed or not. The difference is in the constructability and pre-setup*"-Project Manager.

The interview data reveals that 3d printed components that are of metals and ceramics are durable and strong and their characteristics make them most preferable for the 3D printing construction process which is in line with the findings of Thomas and Gilbert (2014). Their durability and high strength have an impact on the cost of maintenance or replacement of

materials is minimal. Also, the fact that the mentioned components are durable results in buildings that are more durable as compared to buildings constructed using traditional ways. As a result, high strength and durable materials can translate to a higher cost at the initial phase but it reduces the maintenance and replacement costs on the long run of which impacts the overall capital cost and reduces it.

4.2.2. Usability and Applicability

Usability and applicability are other notable characteristics of 3D printing components. As defined in the Literature Review chapter, usability refers to the ease of access and use of a particular product or component. In the context of 3D printing components in the construction industry, it refers to the ease of use of these components in the construction process. Applicability is defined as how useful or appropriate something is for a particular task. In the context of 3D printing components, their applicability points to how useful or appropriate they are for the construction of a façade of an office building. During the study, various aspects of usability and applicability and how they impact the capital cost were explored. The chart below illustrates the concepts that are being explored in the study through the interviews

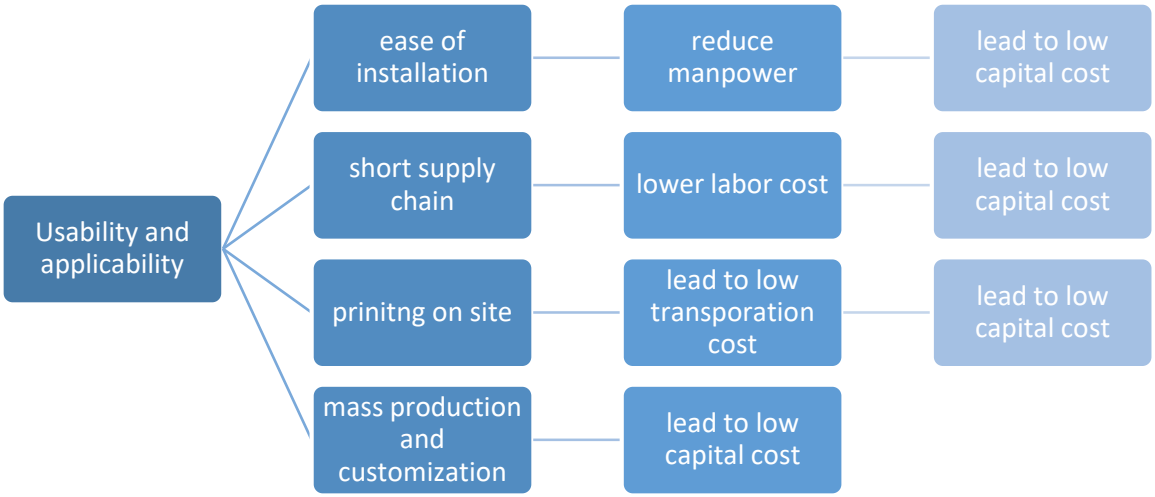

Figure 13: Usability and Applicability Concepts Being Explored Through Interviews (By the Author)

Below are the findings on how the above aspects of usability and applicability impact capital cost of a façade of an office building.

Table 2: Interviewees' Responses on Usability and Applicability Concepts

Interviewees	**Response to Q1**	**Response to Q2**	**Response to Q3**	**Response to Q4**	**Response to Q5**	**Response to Q6**
1	Yes, it will reduce the manpower, which will reduce the cost of using manpower although will increase the cost of machine installation.	No, it will cost more according to the shortage of resources.	Yes, it will reduce the cost and time.	Yes, it will reduce according to the less elements being used.	Yes, it will reduce the cost that will not use connections	No. it will increase cost in terms of material, time and design
2	Yes, unlike traditional manufacturing where many different people may be required to operate a number of machines or a	Yes, 3D printing in the supply chain to increase operational excellence as well as to improve the customer experience.	Yes, 3D printing delivers a lower amount of waste than traditional manufacturing.	When using 3D printing for manufacturing, the labor costs are significantly lower as there is no need for skilled	In majority of mass production needs, 3D printing delivers a lower amount of waste than traditional manufacturing.	Yes, lower number of production steps design, prototype and manufacture highly complex and/or

	production line is required to piece together the product, while 3D printing removes this.			machinists or operators to form part of the process.		customized products.
3	Yes, it will, if we exchanged 100 labors by a 3D printer then it will of course reduce the capital cost	Yes, it does, printing the supply will be cheaper	Yes, because it will save cost and money of the transportation.	Yes, since the required parts are going to be printed this will reduce the cost.	Maybe not, because the demand may not match the mass production.	Maybe it will because customization means producing something new so it will cost more
4	It will not reduce the capital cost till this new 3d print techniques to be common in the construction field.	As soon as 3dprinting in construction being common method it will lower the capital cost related to the short supply chain.	No, as you have to consider the transportation of the 3d print core material as the base for the 3d print method instead of the current material transportation.	I don't think it will reduce the production cost to that limit.	May be mass production is the solution to reduce the cost of 3d printing in the construction field.	It will not inhabit the lowering of the capital cost as the time for any 3d printed part not depend on its complexity of shape but on its volume and Material Mass to be produced.
5	Yes, since the reducing of the labor, it will reduce the capital cost.	It will lower the cost since less entities' profits.	Sure, it will reduce the cost of transportation because it will be printed on site	Yes, it will be low cost.	Yes, less workmanship, less transportation.	The 3D printing can print any custom design without affecting the cost.
6	Yes, it will reduce human resources, transportation , and time, which will reduce the cost	Since it's printed on site it reduces the supply chain itself and mitigate the risk of any damages that may happen during transportation .	Yes, it reduces the transportation cost and any transportation accident that may lose the whole product.	Considering less usage of human resources, supply chain, transportation, accuracy of material will reduce the cost.	Depends on the unit of material (quantity, hours, power) being used the capital cost will be influenced by the quantity.	It will lower the cost because of the technology used in printing the component.
7	True, ease of installation always reduces the cost.	False, there are few companies involved with 3D printing of structure. This mean, few companies can provide the supply, which lead to increase in the price.	Yes, if material is printed on site, there is less chance the item getting damage through transportation.	Yes, if cost of 3D printing is less than traditional method, than the capital cost will be lower and reduced.	Yes, mass production can be achieved if items are being printed fast enough, which will lead to reduction in capital cost.	3D print can be customized to any shape easily, it is not related to the capital cost in my opinion.

8	It could reduce the installation cost; however, it is not a definite straight forward answer.	If the components are printed onsite or close to, then the risk in logistics as a part of supply chain is mitigated, probably transportation cost is saved.	If the elements are printed on site, then transportation cost can be deducted.	It will obviously directly influence the capital cost.	Compared to conventional production lines and risk involved in machines' downtime and logistics, 3D printing could require less capital investment.	3D printing is customization friendly methodology compared to conventional production methodologies . Hence, it is cheaper.
9	Either Yes or No is correct; i.e. reducing the workforce is a factor, however it has to be balanced with the cost of providing high skilled labor with capabilities of performing the activity of installation and production	Yes, less involvers in the production process should significantly lower the capital cost.	Yes, provided that no special materials than those "conventionally " required in the process and they should be sourced from unavailable locally material suppliers.	Yes, making this technology a market available should significantly conclude lower capital cost.	Yes, standardization/unificatio n of produced components lower the initial cost of back of house engineering, production and assembly.	Capital cost can be lowered by offering mass customization.
10	Not really, since it needs qualified labors that are not easy to find. However, later on the case might be different.	Theoretically, it could. However, I don't see it happening in practical work examples/ case studies available.	It might, depending on the availability of the materials.	Yes , by using less resources and labors definitely the capital cost will reduce	Yes, in a way it does by printing unified components.	I don't think it will influence the cost, but as I said earlier skilled labors are hard to find so the assembly might raise the cost.

4.2.2.1 Ease of Installation

A big percentage of the interviewees said that the ease of installation of 3D printing elements reduces the manpower or labor required.

Interviewee 1 stated that:

> "*It will reduce the manpower, which will reduce the cost of using manpower although will increase the cost of machine installation*"-Project Manager.

Interviewee 2 affirmed that:

"*Unlike traditional manufacturing where many different people may be required to operate a number of machines or a production line is required to piece together the product, while 3D printing removes this*"-Project Manager.

Interviewee 6 agreed that:

"*It will reduce human resources, transportation, and time, which will reduce the cost*"-Architect.

On the contrary, a few interviewees argued that the ease of installation of 3D printing elements does not reduce the capital cost.

Interviewee 4 stated that:

"*It will not reduce the capital cost till this new 3d print techniques to be common in the construction field*"-Principal Architect.

Interviewee 10 said:

"*Not really, since it needs qualified labors that are not easy to find. However, later on the case might be different*"-Project Manager.

The interview findings are in line with the findings of Thomas and Gilbert (2014) and Rael and San Fratello (2011) that the process of 3d printing is automated, which reduces manpower and construction time. Moreover, the materials being produced on site translates to lower transportation cost as well. This reduction in manpower required leads to low capital cost.

4.2.2.2 Short Supply Chain in 3d printing components

A majority of interviewees agreed that a short supply chain in 3D printing components lowers the labor cost and transportation cost required. Interviewee 6 and 8 added that the short supply chain will mitigate any risks since its produced-on site.

Interviewee 6 stated that:

"*Since it's printed on site it reduces the supply chain itself and mitigate the risk of any damages that may happen during transportation*"-Architect.

Interviewee 8 agreed that:

"If the components are printed onsite or close to, then the risk in logistics as a part of supply chain is mitigated, probably transportation cost is saved"-Area Manager.

However, interviewee 1 and 7 disagreed claiming that shortage of resources and minimal 3d suppliers will eventually increase the cost.

Interviewee 1 said that:

"No, it will cost more according to the shortage of resources"-Area Manager.

Interviewee 7 affirmed that:

"*False, there are few companies involved with 3D printing of structure. This mean, few companies can provide the supply, which lead to increase in the price*"-Senior Researcher

The interview data supports the finding of Thomas and Gilbert (2014) that 3d printing influences the supply chain management in the construction industry as it is likely to reduce the need for the purchasing, operations, and distribution of materials within the industry.3D printing technology can convey the producers and various construction materials faster to construction companies or sites thus reducing the links in the supply chain. Thus, this shortage leads to low capital cost when 3D printing components are used in construction.

4.2.2.3 Printing 3d printed components On-Site

Almost all of the interviewees confirmed that the printing of 3D printed components usually occurs on-site, and thus reduces the cost of transportation, and ultimately the capital cost. Interviewee 1 stated that:

> "*Yes, it will reduce the cost and time*" -Project Manager.

Interviewee 3 said:

> "*Yes, because it will save cost and money of the transportation*"- Senior Engineer

Interviewee 5 stated that:

> "*It will reduce the cost of transportation because it will be printed on site*"-Principal Architect.

However, interviewee 4 disagreed stating that:

> "*No, as you have to consider the transportation of the 3d print core material as the base for the 3d print method instead of the current material transportation*"-Principal Architect.

The interview findings are in line with the findings of Thomas and Gilbert (2004) that printing the materials on site leads to low costs incurred in transportation of the materials to the construction site. Low transportation cost in turn leads to low capital cost.

4.2.2.4 Mass Production and Customization

Most of the interviewees stated that mass production of 3D printed components reduces a number of factors such as manpower, wastage, and others. In turn, the reduction in these factors leads to low capital cost.

"*In majority of mass production needs, 3D printing delivers a lower amount of waste than traditional manufacturing."* – Project Manager.

"*Mass production can be achieved if items are being printed fast enough, which will lead to reduction in capital cost*"-Senior Researcher.

"*Yes, standardization/unification of produced components lower the initial cost of back of house engineering, production and assembly*"- Project Manager.

Almost half of the interviewees stated that customization of 3D printed components inhabits the lowering of the capital cost with the other half stating that customization of 3D printed components lowers the transportation, installation, and usage of materials.

Interviewee 6 stated that:

"*Customization lowers number of production steps design, prototype and manufacture highly complex and/or customized products*"-Architect.

Interviewee 3 in agreement stated that:

"*Maybe it will because customization means producing something new so it will cost more*"-Senior Engineer.

Based on the interviewee findings, one of the benefits of 3d printing is mass production without interference with customization that is in line with the argument of Wu, Wang, and Wang (2016). Several companies aim to assure mass customization of which products are designed and printed for customers based on their orders and desires "order to build" by using less resources, materials, and wastes. In addition to that, since 3D printers are produced easily through an order, customization varies from simple to highly complex since this won't alter any additive costs. As a result, mass production and customization can translate to lower costs.

4.2.3. Maintainability

Maintainability is an important characteristic of 3D printing components. In the Literature Review chapter, the term “maintainability” is defined as the probability of performing a successful repair or maintenance action for a particular component within a given time. It can also be defined as the ease and speed with which a given component can be kept at operational status. It is a typical characteristic of 3D printing components used in the construction of façade of an office building. The below chart will illustrate the concepts that are being explored through interviews.

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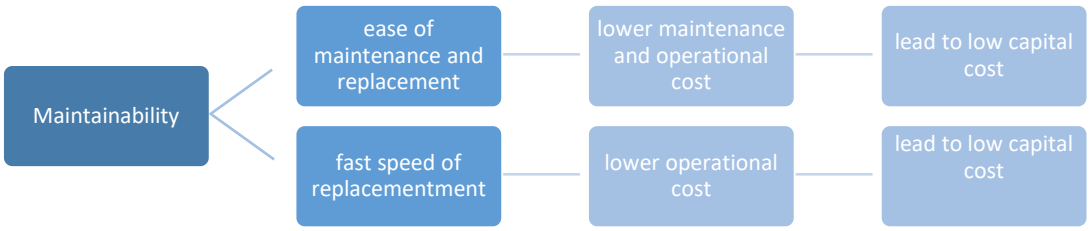

Figure 14: Maintainability Concepts Being Explored Through Interviews (By the Author)

The findings on how maintainability impacts capital cost of a façade of an office building are presented in the table below.

Table 3: Interviewee's Responses on Maintainability Concepts

Interviewees	Response to Q1	Response to Q2
1	Yes, that we have components in 3d printing the easy for replacement.	It will not affect too much according to the machine work.
2	Yes, the whole production line can be adjusted and adapted with the speed of the printing production line.	Durability of the components requires less maintenance, less resources and manpower, which reduces the operational cost.

3	Yes, it is much faster than the traditional way.	I believe it will lower the cost.
4	Sure, replacing 3d printed part will be so easier and it will be no need for keeping the extra material resources within the construction itself as it will be ordered later in case of need only.	Just order the required replace part or just click on print for the model in case of the availability of the printer in the near locations.
5	The 3D printing will reduce the cost and reduce the maintenance.	It will be easier to maintain and to replace.
6	The product will be available in a very short time of which speeds up the replacement process.	After the component is printed it considered a material after all if its high-quality material it will increase the service life of the product which will eventually will reduce the operational cost and future replacements.
7	Yes, since using 3D printing allow less maintenance item to be stocked and printing the required item if needed.	It helps a lot with maintenance, since item are not stocked, and the maintenance can be printed on site directly.
8	Usually speed of maintenance is related to availability of spare parts, fixation details, the simpler fixation detail is the faster installation is resulted.	If the material used is durable and reliable then it will have a longer life span in which maintenance/replacement requirement will be less.
9	Some materials are durable enough to eliminate often maintenance, as well as its ease of production speeds up the replacement.	Provided that different considerations of the components than those if conventionally produced, then operational cost has to be reviewed accordingly.
10	It depends whether the 3d component was pre-programmed in the setting or the need to program it all over again.	Pre-programming of the components should make efficient

4.2.3.1 Ease of maintenance and replacement of 3d printed components

Almost all of the interviewees stated that 3D printed components are accompanied by the ease of maintenance and replacement since they can be printed directly on site rather than being stocked, and the printed material is durable so this translates to higher service life which reduces the maintenance cost.

Interviewee 1 was not against but claimed that:

"*It will not affect too much according to the machine work*"-Project Manager.

Interviewee 2 stated that:

"*It will be easier to maintain and to replace*"-Project Manager.

The interview data reveals that with easier maintenance and replacement, there is lower maintenance and operational cost (Canas, 2014). This then leads to low capital cost.

4.2.3.2 Fast Speed during replacement of 3d printed components

A good number of interviewees associated 3D printed components to fast speeds particularly during replacement, as interviewee claimed:

> "*the whole production line can be adjusted and adapted with the speed of the printing production line*." – Project Manager.

Interviewee 10 said that the speed is dependent on the programming of the software:

> "*It depends whether the 3d component was pre-programmed in the setting or the need to program it all over again"*-Project Manager.

However, as a researcher claim, components are already designed on software and printed as per the design. Fast speeds during replacement because of its ease of production translates to lower operational cost, which then leads to low capital cost. 3D printing components used in the construction process can be replaced faster thus reducing operational costs and ultimately the capital cost incurred (Perkins and Skitmore, 2015).

4.3 The Impact of 3D Printing Components on Operational Cost

The next step in the analysis is to determine the characteristics of 3D printing components that impact the operational cost of a façade of an office building. In the Literature Review chapter, the two major characteristics or aspects explored are replacement and maintenance.

4.3.1 Replacement

As explored in the Literature Review chapter, replacement is one of the key concepts that impact operational cost of a façade of an office building. The below illustration will reveal the concepts that are being explored through interviews.

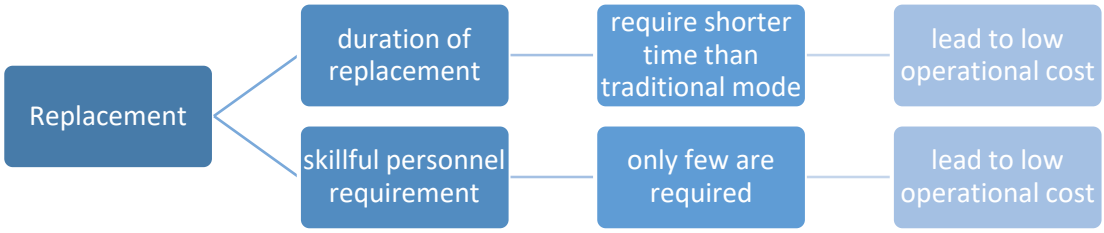

Figure 15: Replacement Concepts Being Explored Through Interviews (By the Author)

The findings on how replacement impacts operational cost of a façade of an office building is presented in the table below.

Table 4: Interviewees' Responses on Replacement Concepts

Interviewees	**Response to Q1**	**Response to Q2**
1	It will take shorter time in replacing the components of the 3D printing façade that depends on managing the machine.	Yes, need a special skill in managing the program of the printer to stop and replace.
2	Replacement of 3D printed components takes shorter time in comparison to the replacement of components used in traditional modes because 3d printer requires less process, labor, equipment's, and material.	No, there is no need for skilled machinists or operator to form part of the process.
3	It will take shorter time as compared to the replacement of components or materials used in traditional modes.	No, I don't think so it requires since the printer prints the components accordingly.
4	I think it will be shorter and replacement will be done 100% as required and as per the original parts.	After print the part regular skilled person will be enough for the replacement procedures.
5	In 3D printing, the replacement will be faster, and less cost, since no transportation and less workmanship.	It need only the 3D designer, no professional or skillful labor.
6	It's going to be shorter because the production of the components will be faster by printing it.	Yes, a skilled technician is a must to replace any part to avoid any damages.
7	The replacement should be faster, since the printer will be on site and ready to print. If the printer is not in the site, it will take longer.	A skillful person is required, since handling 3D printing in large scale required certain pre setup that should be followed.
8	The replacement is directly related to the complexity of the fixation details and accessibility, so speed of installation/replacement may vary.	It does require specialized skilled personnel to produce, furthermore, skilled personnel are needed for any type of jobs.
9	Provided that the 3D Printed Components have different considerations than those if they have been conventionally produced, then different methodologies	Provided that the 3D Printed Components have different considerations than those if they have been conventionally produced, then different methodologies

	have to be generated in order to accommodate/maintain/de-assemble/deal with the components.	have to be generated in order to accommodate/maintain/de-assemble/deal with the components.
10	Shorter time if it is pre-programmed. Longer if we need to do the setup and programming	Yes. Someone able to understand the engineering behind it as well. However, if the information is pre-programmed so not really.

4.3.1.1 Duration of Replacement

Several interviewees confirmed that the replacement of 3D printed components or materials used in the construction of a façade of an office building takes a shorter time as compared to the time taken in replacing components or materials used in traditional modes of construction. Majority confirmed that the replacement time would be shorter due to the ease and fast production of 3d printed components specially when printed on site.

Interviewee 2 claimed:

> "*Replacement of 3D printed components takes shorter time in comparison to the replacement of components used in traditional modes because 3d printer requires less process, labor, equipment's, and material.*" – Project Manager.

Interviewee 3 stated that:

> "*It will take shorter time as compared to the replacement of components or materials used in traditional modes*"-Senior Engineer.

Interviewee 5 argued that:

> "*In 3D printing, the replacement will be faster, and less cost, since no transportation and less workmanship*"-Principal Architect.

2 other interviewees stated that the replacement time is going to be shorter under certain conditions, whether the components are being directly printed on site and if its pre-programmed for printing.

Interviewee 7 affirmed that:

> "*The replacement should be faster, since the printer will be on site and ready to print. If the printer is not in the site, it will take longer*"-SR Researcher.

The interview data indicates that a benefit of 3d printing components that it produces components very fast, since it's a machine that prints directly into any form through a single click, the flexibility of customization in design is beneficial and doesn't influence the cost. On the contrary of the traditional mode that requires workforce, material, transportation and installation will require extra time in providing a casting mold if the material was concrete or delivery and transportation time depending on the availability of the products needed. However, the shorter time required in replacement leads to lower operational cost (Thomas and Gilbert, 2014).

4.3.1.2 Skillful Personnel Requirement

A major group of interviewees agreed that specialized skillful personnel are required for replacement of 3D printed components. The interviewees urged that the skillful personnel are required for programming purposes to assure smooth printing with no risks or errors specially when printing at a large scale. However, they stressed that only few skillful personnel are required, which leads to low operational cost.

Interviewee 1 agreed that:

> "*There is need of a special skill in managing the program of the printer to stop and replace*" -Project Manager.

Interviewee 6 agreed that:

> "*A skilled technician is a must to replace any part to avoid any damages*"-Architect.

Interviewee 10 affirmed:

> "*Someone able to understand the engineering behind it as well. However, if the information is pre-programmed so not really*"-Project Manager.

A few interviewees claimed that it is not necessary for skilled personnel, since the production is fast and easy.

Interviewee 2 stated that:

> "*There is no need for skilled machinists or operator to form part of the process*"-Project Manager.

Interviewee 3 stated that:

> "*I don't think so it requires since the printer prints the components accordingly*"-Senior Engineer.

The interview findings reveal that the technology mainly uses AutoCAD as a software to be designed on and printed from, along with different softwares. However, AutoCAD is commonly used in the construction industry and is familiar among professionals in the field to produce drawings based on a particular design. On the other hand, traditional modes of construction rely heavily on the skills of individuals in order to produce projects with the desired quality of which consumes skilled workforce. Based on that the less skilled technicians and labors required the lower the operational costs (Thomas and Gilbert, 2014).

4.3.2. Maintenance

Maintenance is another important concept that impacts the operational cost of a façade of an office building. The two concepts that are exemplified in the chart below are explored through the interviews

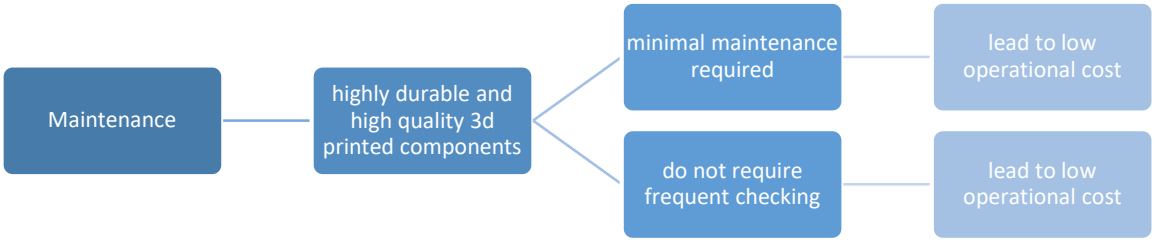

Figure 16: Maintenance Concepts Being Explored Through Interviews (By the Author)

The findings on the above questions are presented in the table below.

Table 5: Interviewees' Responses on Maintenance Concepts

Interviewees	**Response to Q1**	**Response to Q2**
1	In 3d printing technique it has lower cost comparing to the traditional way of construction according to the labor and materials.	Yes, the frequent checking and maintenance of the 3d printing façade will raise the operational cost according to the machine and manpower.
2	The maintenance cost can reach thousands of dollars yearly depending on the nature of the project. Maintenance cost doesn't translate to high operational cost.	Frequent checking is not required. on a yearly basis maintenance if needed.
3	It depends on the nature and size of the project; it translates to low operational cost.	It requires frequent checking and yes it will increase the cost depending on how many numbers of maintenance is required.
4	Will be as regular as the current method of ongoing maintenance cost.	No extra frequent maintenance procedures required, just regular checking workflow will be ok, so no increase in cost.
5	The maintenance cost translates to low operational cost.	3D printing doesn't require frequent maintenance, which will reduce the operational cost.

6	If it's a good product of a high quality it will reduce the estimated cost this translate to lower operational cost.	Frequent checking is a must, but replacing the components may not be needed due to the quality of the products.
7	The printing of the maintenance items leads to a lower operational cost.	It all depends on the quality of the printed part, if the quality of the printed part is high. It doesn't require a lot of maintenance, which ultimately lead to a lower operational cost.
8	If technology is available then should be less, however, might be the opposite in case of non-availability.	Depends on the material and workmanship, however, it is newly introduced then I would expect more often regular check-ups, this may not be a significant increase of OPEX.
9	Yes, maintainable components, easy to de-assemble and reassemble significantly results into lower operational cost.	Provided that a 3D Produced Component is more durable than if it is conventionally produced then high durability is inversely proportional with the frequency of maintenance and that will translate into lower cost of maintenance.
10	It depends on the quality of the material being utilized; I think it will reduce the cost.	Not as frequent as normal methods given the engineering and efficient use of materials and components.

4.3.2.1 Highly Durable and High-Quality 3d printed Components

Several interviewees stated that 3D printed components are highly durable and are of high quality hence require minimal maintenance and less frequent checking as compared to components or materials used in traditional modes of construction that require frequent checking and maintenance.

Interviewee 9 stated that:

> "*Provided that a 3D Produced Component is more durable than if it is conventionally produced then high durability is inversely proportional with the frequency of maintenance and that will translate into lower cost of maintenance*." - Project Manager.

A few interviewees opposed the argument that frequent checking is required due to the quality and workmanship of the components being maintained of which increases the maintenance cost.

Interviewee 5 stated that:

"*3D printing doesn't require frequent maintenance, which will reduce the operational cost*"-Principal Architect.

Interviewee 10 stated that:

"*Not as frequent as normal methods given the engineering and efficient use of materials and components*"-Project Manager.

Based on the interview findings, a benefit of 3d printing is producing highly durable and high-quality printed components translate to an increase of their service life, therefore reduces the maintenance and operational cost. However, some of the interview data reveals that some materials such as metals and aluminums translate to higher costs of production and maintenance. This is because those constructive materials are produced by selective laser sintering technique type which raises the maintenance and operational costs 10 times when it comes to replacing a single component as opposed to the conventionally produced that is cheaper (Paudyal, 2015). However, this study was investigated and explored through interviews and it concludes that highly durable printed components with high quality requires less frequent checking and maintenance, which reduces the operational costs.

As stated by interviewee 7:

"*It all depends on the quality of the printed part, if the quality of the printed part is high. It doesn't require a lot of maintenance, which ultimately lead to a lower operational cost*." – SR Researcher.

This concludes that with minimal maintenance and less frequent checking required both lead to low operational cost.

CHAPTER 5- DISCUSSION AND CONCLUSION

5.1 Introduction

In this chapter, a discussion and conclusion will be presented to highlight the major findings of the impact of 3D printing components on the capital and operational cost of a façade of an office building. The discussion sub-chapter is a cross analysis aimed at comparing the outcomes or findings of the study with the results of previous studies and literature explored in the Literature Review Chapter. In the conclusion sub-chapter, the major implications of the research are highlighted. Also, there is a conclusion that presents the major findings of the study on the impact of 3D printing components on the capital and operational costs of a façade of an office building. The conclusion sub-chapter also entails a brief description of the research contribution and limitations. A number of recommendations are also listed to further expand the research on the topic.

5.2 Discussion

5.2.1 3D Technology

3D printing technology has been around for almost 4 decades now having been created in the 1980s when Charles W. Hull created the first working 3D printer. In the 1980s when 3D printing technology was developed, it was quite expensive and could not be used for commercial purposes. According to Canas (2014), the use of the technology gradually spread in a number of sectors including the construction sector. Head (2017) argues that the adoption of 3D printing technology in the construction industry resulted in construction firms finding it unnecessary to create physical models in construction processes. From2000 to present, there has been full-scale practical application of 3D printing technology in the

construction industry. According to Paudyal (2015), 3D technology can be categorized into six different types including stereolithography (SL), selective laser sintering (SLS), selective laser melting (SLM), electron beam melting (EBM), laminated object manufacturing (LOM), and fused deposition modeling (FDM). These types of 3D printing technology have played a key role in improving various sectors such as the construction sector.

According to Perkins and Skitmore (2015), the adoption of 3D printing technology in the construction industry has greatly benefited the industry particularly from the perspective of capital cost. When used in construction projects, 3D printing technology helps in the reduction of wastage. Research on this shows that the construction industry alone generates huge amounts of waste with estimations of between 3 and 7 tons of waste being generated when constructing a home for a single family. This is coupled with harmful emissions generated during the construction process. However, these challenges have been addressed with the use of 3D printing in construction. The technology produces only what is required for the construction of the final structure. Other benefits of 3D printing technology to the construction sector are the reduction in the speed of producing final products or materials used in the construction process, on-site printing of 3D printed components that reduces the transportation costs and time, the creation of more efficient and interesting designs as the technology can come up with desirable shapes and designs that cannot be created by traditional construction models, as well as mass production and customization that are of importance in the construction sector.

5.2.2 Factors Influencing Capital Cost of 3D building components

Capital cost is defined as the cost associated with the procurement of 3D printed components, transportation to site, construction, as well as installation. According to Thomas and Gilbert (2004), capital cost in the construction industry are well-structured cost such as labor, material, and machine costs as well as ill-structured costs such as inventory, build failure, and setup. Factors influencing the capital cost of 3D printing include durability, usability, applicability, and maintainability of the 3D printed components.

Concerning durability, the primary aim of using 3D printing technology in construction is to have strong and durable houses. Canas (2014) argues that this objective is achieved because of the strong and durable 3D components used. Thus, the durability of 3D printed components reduces capital cost as minimal maintenance and operation is required. As discussed in the LR, usability and applicability point to the easy use of 3D printed components during the construction process (Rael and San Fratello, 2011). This is hardly witnessed in traditional building models. With the aspects of usability and applicability, the capital cost required in terms of labor and production is lower as compared to the capital cost required in traditional building models. Maintainability of 3D printed components also influences the capital cost in the construction process. As discussed in the LR, metals are the most commonly used 3D printed components in construction because of their maintainability. Some of the commonly used metals in construction are aluminum, cobalt derivatives, and stainless steel (Janssen, Blankers, Moolenburgh, and Posthumus, 2014). Maintainability of these components translates to ease and fast speeds during construction process thus reducing the capital cost.

5.2.3 Factors Influencing Operational Cost Of 3D Building Components

Operational costs are costs required for the day-to-day functioning and maintenance of a construction project. These costs include administrative as well as maintenance, replacement, and repair costs. According to Thomas and Gilbert (2014), operational cost in the construction industry mainly entails costs required or used in maintenance and replacement of building components. When 3D printed components are used in construction, the duration of replacing these components when there is need to do so is usually shorter as compared to the duration or time required in replacement of components in traditional building models. With the shorter duration or time required in replacement of 3D printed components, the operational cost is significantly lowered. Moreover, unlike in replacement of components in traditional building models where a number of personnel are required, the replacement of 3D printed components used in construction requires only few personnel thus leading to low operational costs. Maintenance of 3D printed components is also an important factor influencing operational costs. Thomas and Gilbert (2014) argue that 3D printed components are durable and high-quality, and thus, they require minimal or less frequent maintenance as compared to components used in traditional building models. As such, the cost of maintenance is lower, which translates to low operational costs.

5.3 Discussion of Findings from Capital Cost

In the study, the impact of 3D printed components on capital cost was explored from the perspectives of durability, durability, usability and applicability, as well as maintainability.

5.3.1 Durability

The analysis of the findings shows that various aspects of durability such as production, increased service life of 3Dprinted components, and the high strength of the components all impact the capital cost.

5.3.1.1Production of 3d Printed Components

The findings show that a majority of the participants agreed that the aspect of production, which is under the characteristic of durability, has an influence on the capital cost. A majority of the participants interviewed agreed that in the production of 3D printed components, there is usage of less resources and less wastage of material. Based on the analysis, 3D printed components require less use of resources in production. The production of components through 3D printer is much easier and requires fewer workforces, material, and waste as compared to the traditional mode. The technology of the machine is designed to print a component through a layering process that produces durable components with an efficient amount of material being used printed into any shape desired. This is correlated to the waste management; the less material being utilized the lower the waste and the cost. The less usage of resources and less wasted material in production of 3D printed components lead to low capital cost. This finding is supported by researchers such as Thomas and Gilbert (2014) and Canas (2014).

5.3.1.2 Increased Service Life of 3D Printed Components

The findings show that several interviewees agreed that an increased service life of 3D printed components means less maintenance and capital cost. The majority agreed that agreed that increasing the service life of the components decreases the capital cost as a result of less maintenance required. Based on the analysis, producing very high durable materials may increase the cost in the short term but it will benefit a reduction of the maintenance and replacement cost that will impact the overall capital cost to be lower. This is achieved through the ease of production of the components since it is a "build through order" process that is designed through a software and being printed immediately on site. This eases the replacement and maintenance of the parts away from the complexity of creating casting molds or assembly aspects. Based on that time is saved, long run cost is maintained, and material is utilized efficiently. Essentially, an increase in the service life of 3D printed components causes a decrease in the maintenance and operational costs that ultimately leads to low capital cost. This result supports the findings of Thomas and Gilbert (2014) that durability of 3D components reduces the capital cost. Canas (2014) also supports these findings through the argument that increasing the service life of 3D printed components influences a decrease in capital cost.

5.3.1.3 Producing High-Strength Components

The results show that a majority of the interviewees stated that producing high-strength 3D components results in high capital cost. Based on the analysis, high-strength and durable 3D printed components lead to higher cost at the start although this reduces the maintenance and replacement costs in the long run thus reducing the overall capital cost. This finding is

supported by Thomas and Gilbert (2014) who argue that high-strength 3D components are durable and require low maintenance costs leading to low capital cost.

5.3.2 Usability and Applicability

The analysis of findings reveals that various aspects of usability and applicability impact the capital cost. These aspects include ease of installation, short supply chain, printing on-site, as well as mass production and customization.

5.3.2.1 Ease of Installation

The findings show that a big percentage of the interviewees affirmed that the ease of installation of 3D printed elements reduces the manpower or labor required. Only a few argued that the ease of installation or 3D printed elements has no impact on labor or manpower required. Based on the analysis, the process of 3D printing is automated, which reduces the manpower and construction time. The reduction in manpower required leads to low capital cost, a finding supported by researchers such as Thomas and Gilbert (2014) and Rael and San Fratello (2011).

5.3.2.2 Short Supply Chain in 3d printing components

The interview data reveals that a majority of interviewees agreed that a short supply chain in 3D printing components lowers the labor cost and transportation cost required. Based on the analysis, 3D printing tends to influence the supply chain management in the construction industry. This is because 3D printing reduces the need for purchasing, operations, and distribution of materials within the industry. 3D printing technology can convey the producers and various construction materials faster to construction companies or sites thus

reducing the links in the supply chain. This is in line with the finding of Thomas and Gilbert (2014) that a short supply chain leads to low capital cost. The finding is also consistent with the findings of Janssen, Blankers, Moolenburgh, and Posthumus (2014) in the LR.

5.3.2.3 Printing 3d components On-Site

The analysis reveals that almost all interviewees agreed that the printing of 3D components usually occurs on-site thus reducing the cost of transportation and ultimately the capital cost. Based on this data, printing on-site lowers the capital cost which is consistent with what Thomas and Gilbert (2014) found about the impact of printing on-site on the capital cost in the construction industry. The finding is also supported by Poullain, Paquet, Garnier, and Furet (2018) in their argument that the on-site deployment of 3D printing for the building and construction industry helps to reduce the capital cost.

5.3.2.4 Mass Production and Customization

An examination of the analysis reveals that most of the interviewees stated that mass production of 3D printed components reduces a number of factors such as manpower, wastage, and others. The findings also reveal that almost half of the interviewees stated that customization of 3D printed components inhabits the lowering of the capital cost whereas the other half stated that customization of 3D printed components lowers the transportation, installation, and usage of materials. Based on the analysis, both mass production and customization of 3D components reduce the capital cost, and this finding is supported by Wu, Wang, and Wang (2016).

5.3.3 Maintainability

From the analysis, two aspects of maintainability tend to have an impact on the capital cost. These aspects include ease and fast speed.

5.3.3.1 Ease of maintenance and replacement of 3d printed components

By examining the analysis, it is found that almost all of the interviewees stated that 3D printed components are accompanied by the ease of maintenance and replacement since they can be printed directly on site rather than being stocked, and the printed material is durable so this translates to higher service life which reduces the maintenance cost. Based on this analysis, easier maintenance and replacement of 3D printed components lowers the maintenance and operational cost. In turn, this leads to low capital cost which is consistent with the finding of Canas (2014).

5.3.3.2Fast Speed of replacement of 3d printed components

The analysis found that several interviewees associated 3D printed components to fast speeds particularly during replacement. Based on the analysis, fast speeds witnessed during replacement because of the ease of production tend to lower the cost incurred in operation, which then leads to low capital cost. 3D printing components used in the construction process can be replaced faster thus reducing operational costs and ultimately the capital cost incurred. This finding is supported by Perkins and Skitmore (2015) in the literature review.

5.4 Discussion of Findings from Operational Cost

In the study, the impact of 3D printed components on operational cost was explored from the perspectives of replacement and maintenance.

5.4.1 Replacement

An examination the analysis reveals that two aspects of replacement have an impact on the operational cost. These aspects are the duration of replacement and skillful personnel requirement.

5.4.1.1 Duration of Replacement of 3d printed components

From the analysis, several interviewees confirmed that the replacement of 3D printed components or materials used in the construction of a façade of an office building takes a shorter time as compared to the time taken in replacing components or materials used in traditional modes of construction. Majority confirmed that the replacement time would be shorter due to the ease and fast production of 3d printed components specially when printed on site. Based on this analysis, a benefit of 3D printing components is that they are produced very fast since the 3D printing machine prints directly into any form through a single click, the flexibility of customization in design is beneficial and does not influence the cost. Thus, the shorter time required in replacement leads to lower operational cost; a finding supported by Thomas and Gilbert (2014) in the LR. Moreover, in the LR, Rouhana, Aoun, Faek, Eljazzar, and Hamzeh attribute the reduction of the construction duration to the implementation of 3D printing, which then reduces the operational cost.

5.4.1.2Skillful Personnel Requirement

Based on the interview analysis, a major group of interviewees agreed that specialized skillful personnel are required for replacement of 3D printed components. The interviewees urged that the skillful personnel are required for programming purposes to assure smooth printing with no risks or errors specially when printing at a large scale. However, they stressed that

only few skillful personnel are required, which leads to low operational cost. An explanation for this finding is that the few skilled technicians and laborers required lower the operational cost, which proves the results of Thomas and Gilbert (2014) and Paudyal (2015) in the literature review section.

5.4.2 Maintenance

A review of the analysis reveals that an aspect of maintenance that impacts the operational cost is the high-durability and high-quality of 3D printed components.

5.4.2.1Highly Durable and High-Quality Components

Basing on the interview analysis, several interviewees stated that 3D printed components are highly durable and are of high quality hence require minimal maintenance and less frequent checking as compared to components or materials used in traditional modes of construction that require frequent checking and maintenance. An explanation for this finding is that minimal maintenance and less frequent checking required leads to low operational cost as stated by Paudyal (2015) in the LR.

5.5 Conclusion

5.5.1 Research Conclusion

This dissertation explores the impact of 3D printing components on the capital and operational cost of a façade of an office building. The factors or aspects of 3D printing components impacting the capital cost of a façade of an office building include durability, usability and applicability, as well as maintainability. The factors or aspects of 3D printing components impacting the operational cost of a façade of an office building include

replacement and maintenance. Overall, based on the analysis, it can be concluded that 3D printing components impacts the capital and operational cost of a façade of an office building in various ways.

- The durability of 3D printed components influences production, increases service life of components, and results in high-strength components. These then trigger the usage of less resources, less wasted material, less maintenance and operational cost, all of which lead to low capital cost.
- The usability and applicability of 3D printed components influence ease of installation, shortens the supply chain, allows on-site printing, and facilitates mass production and customization. These then cause a reduction in manpower, lower labor cost, low transportation cost, all of which lead to low capital cost.
- The maintainability of 3D printed components allows easy maintenance and replacement and fast speeds during replacement. In turn, these cause lower maintenance and operational cost that ultimately lead to low capital cost.
- The ease of replacement of 3D printed components reduces the duration of replacement and reduces the skillful personnel required thus leading to low operational cost.
- The ease of maintenance of 3D printed components is a result of the highly durable and high-quality components. Thus, the components require minimal maintenance and do not require frequent checking thus leading to low operational cost.

5.5.2 Research Implications

The findings from the analysis respond to the research question and helps to achieve the research goals that are to investigate the 3D printing technology usage in producing 3D components for a façade; investigate how 3D printing can reduce capital cost; investigate how 3D printing can reduce maintenance cost; and seek the opinion of experts on 3D printing with a view to reduce capital cost and operational cost. The findings have significant implications particularly for the construction industry. The implication of the research findings is that the construction industry as a whole should consider adopting the use of 3D printing technology. This could help revamp the construction industry and make the construction process not only easier but also less expensive in terms of the low capital and operational costs.

5.5.3 Limitations

This study is affected by multiple limitations and challenges that to some extent influence the outcomes. The limitations of the research are as follows:

- The data collected was limited to only 10 participants, mainly in Dubai. Thus, the outcomes may not be generalized to the overall U.A.E population.
- Some participants did not have a clear understanding of some of the concepts in the interview. Thus, they did not respond to some of the interview questions which might interfere with the reliability and validity of the findings.
- The researchers decided who would be participating in the interview and excluded others. A certain level of bias might have been witnessed in the recruitment of the participants.

- There was late response from some participants, which delayed the completion of the research.

5.5.4 Future Research Recommendations

For future research, this dissertation's findings could serve as a basis for building future research. There are some gaps in this dissertation that should be filled by future research. Thus, future research should focus on:

- Obtaining information or insight from more participants to ensure the validity and reliability of outcomes.
- Examining and interviewing construction organizations that are already using 3D printing technology.
- The challenges and opportunities in the use of 3D printing technology.
- Using a quantitative research method or a combination of both qualitative and quantitative methods to collect data.

5.5.5 Research Contribution

This dissertation can make significant knowledge contributions from an academic perspective and construction perspective. The study's findings indicate that there is well-established research on 3D printing technology and how it has impacted the construction industry. Thus, this dissertation contributes to existing knowledge from an academic perspective and adds value about the impact of 3D printing technology on capital and operational cost in construction projects through its presentation of data and evidence of some of the aspects of 3D printed components that influence capital and operational cost. Also,

from an academic perspective, it offers strong evidence that appropriate use of 3D printing technology can lead to numerous benefits to the construction sector.

The major findings of this research for construction experts and the construction industry as a whole is that 3D printing technology reduces the operational and capital cost of construction projects. It also gives an overview of different types of 3D printing technology and how they are used in the construction process. Through this, this research will broaden the knowledge of construction experts and make them aware of the what can be done or avoided when using 3D printing technology in construction.

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Appendices

Appendix A: Data Collection/Interviews

Theme: 1 - Durability

Title: Senior Architecture Engineering

Experience: 5 years

Position: Project Management

Date: 23/3/2019

Location: governmental entity

Interviewer: Maryam AlZarooni

Interviewee: interviewee 1

Q1: What is your opinion on the durability of 3D printing components in a façade of an office building?

Probe: does 3d printed components quality influence capital cost? Does it make it higher?

Answer: the strength of the 3D printing that will be used in office building depends on material, design and height. I think that for time being 3D printing components is durable enough according to the researches; however, this durability will increase capital cost of the building construction in quality and time

Reflective: as the interviewee indicated that durability of the components may increase the capital cost on the time being, but for the long term durable 3d printed components translate to lower maintenance and operational cost which influence the capital cost

Q2: Does 3d printed components require less use of resources in production?

Answer: no, it requires more resources that depends in design and material, less resources in man power

Reflective: 3d printers inhabit different forms and print the requested components without wasting materials

Q3: Does the usage of less material influence the waste management and cost?

Answer: yes, depending on the design or component being printed

Reflective: usage of less resources when prinitng 3d components reduces waste and cost

Q4: Does increasing the service life of 3d components have an influence on the capital cost?

Answer: yes, it will increase the cost that we should use more durable materials

Reflective: increasing the service life will decrease the operational cost and will reduce the overall capital cost

Q5: Does producing very durable strong 3d component lead to high capital cost?

Answer: yes, because more material and time will be consumed

Reflective: high durable material translate to lower maintennce cost which influences the capital cost

Theme: 2 – Usability and Applicability

Q1: Does ease of installation of 3D printing elements reduce the labor or workforce required thus translating to a reduced capital cost required in constructing the façade of an office building?

Answer: yes, it will reduce the manpower, which will reduce the cost of using manpower although will increase the cost of machine installation

Reflective: 3d printers print on site which reduces instalation and manpower costs , thus reducing the capital cost

Q2: Does the short supply chain involved in 3D printing of components contribute to lower capital cost of using 3d printing?

Answer: no, it will cost more according to the shortage of resources

Reflective: since 3d prinitng is becoming a method of construction this translates to lower cost of production and labor work

Q3: Do you think that products or materials are printed on-site thus translating to a significant reduction in the cost of transportation?

Answer: yes, it will reduce the cost and time

Reflective: printing on site reduces transporation cost , time, and equipmemt

Q4: An important perspective of the capital cost in the construction industry is production. Does applicability of 3Dprinting components used in constructing the façade of an office building reduce the cost of production and ultimately the capital cost?

Probe: Does reduced production cost translate to a reduction in the capital cost?

Answer: yes, it will reduce according to the less elements being used

Reflective: ease of production and reduction of material usage translates to reduction of the capital cost

Q5: Does mass production of 3d printed components lower the capital cost?

Answer: yes, it will reduce the cost that will not use connections

Reflective: mass production will reduce manpower cost which lowers the capital cost

Q6: Does customization of 3d printed components inhabit the lowering of capital cost?

Answer: no. it will increase cost in terms of material, time and design

Reflective: 3d printer inhabits different forms and prints on site directly which lowers the transporation, installation , and usage of materials , thus reducing the capital cost

Theme: 3 - Maintainability

Q1: Speed is an important aspect in the construction industry. Do you think the 3d printed components make the operability of maintainability, of which makes the maintenance process easier and increase the speed during the replacement of the façade of an office building?

Answer: yes, that we have components in 3d printing the easy for replacement

Reflective: ease of production and usability of 3d printed components accelerates the replacement of a component

Q2: How do you think maintainability of 3D printed materials/components impact the operational cost of the façade of an office building in terms of ease of maintenance or replacement?

Answer: it will not affect too much according to the machine work

Reflective: 3d printers produce high durable materials which reduces the operational cost

Theme: 4 - Replacement

Q1: Does the replacement of 3D printed components/materials used in constructing the façade of an office building take longer or shorter time as compared to the replacement of components or materials used in traditional modes of construction?

Probe: Is the replacement time shorter or longer for 3D printing materials or components?

Answer: it will take shorter time in replacing the components of the 3D printing façade that depends on managing the machine

Reflective: production of 3d printed components takes shorter time than the traditional methods of which takes a shorter replacement period

Q2: Does the 3d printed components require any specialized skillful personnel for replacement?

Answer: Yes, need a special skill in managing the program of the printer to stop and replace

Reflective: 3d printed component are usable and easily applicable therefore skillful personnel might need to manage the printer program if needed as the interviewee responded but not for the replacement

Theme: 5 - Maintenance

Q1: What is the estimated ongoing maintenance cost for 3D printing components used in constructing the façade of an office building? Does the maintenance cost translate to low or high operational cost?

Answer: in 3d printing technique it has lower cost comparing to the traditional way of construction according to the labor and materials.

Reflective: 3d printed components call for lower operational cost since they are highly durable in comparison to the traditional methods that require frequent maintenance

Q2: How frequent is it required for the maintenance of the façade of an office building constructed using 3D printing technology?

Probe: If frequent checking is required, do you think this raises the cost of maintenance and ultimately the operational cost?

Answer: yes, the frequent checking and maintenance of the 3d printing façade will raise the operational cost according to the machine and manpower

Reflective: 3d printed components are high in quality, which doesn’t require frequent checking

Theme: 1 - Durability

Title: engineer

Experience: 6 years

Position: project manager

Date: 23-03-2019

Location: site office

Interviewer: Maryam AlZarooni

Interviewee: interviewee 2

Q1: What is your opinion on the durability of 3D printing components in a façade of an office building?

Probe: does 3D printed components quality influence capital cost? Does it make it higher?

Answer: Traditional manufacturing methods are expensive, whereas the 3D printing process makes the creation of parts product cheaper and more accessible.

Reflective: 3d printing produces durable high-quality components with lower capital cost

Q2: Does 3d printed components require less use of resources in production?

Answer: Yes, highly sustainability and efficiency in production through using the least amount of material and energy in production.

Reflective: 3d printed components require less usage of resources which reduces cost

Q3: Does the usage of less material influence the waste management and cost?

Answer: Yes, as this a relatively new technology that is gaining momentum the material cost can still remain high. However, the range of materials is growing and this makes it possible for the price to decrease over time.

Reflective: usage of less material at production reduces the waste and cost

Q4: Does increasing the service life of 3d components have an influence on the capital cost?

Answer: No, it doesn't influence the capital cost because more service life of the components less capital we need.

Reflective: increasing the service life of 3d components will result in lower capital and operational costs

Q5: Does producing very durable strong 3d component lead to high capital cost?

Answer: No, when business has the ability to confirm a design before committing it to production, it can be help to remove the risk of errors, wasted materials and money.

Reflective: producing strong durable components with less resources will reduce the capital cost

Theme: 2 – Usability and Applicability

Q1: Does ease of installation of 3D printing elements reduce the labor or workforce required thus translating to a reduced capital cost required in constructing the façade of an office building?

Answer: Yes, unlike traditional manufacturing where many different people may be required to operate a number of machines or a production line is required to piece together the product, while 3D printing removes this.

Reflective: 3d printers are more easible in assembly and requires less manpower

Q2: Does the short supply chain involved in 3D printing of components contribute to lower capital cost of using 3d printing?

Answer: Yes, 3D printing in the supply chain to increase operational excellence as well as to improve the customer experience.

Reflective: the ease of usability and applicabilty of 3d components leads to low cost

Q3: Do you think that products or materials are printed on-site thus translating to a significant reduction in the cost of transportation?

Answer: Yes, 3D printing delivers a lower amount of waste than traditional manufacturing.

Reflective: usage of fewer materials in production of 3d components reduces cost

Q4: An important perspective of the capital cost in the construction industry is production. Does applicability of 3Dprinting components used in constructing the façade of an office building reduce the cost of production and ultimately the capital cost?

Probe: Does reduced production cost translate to a reduction in the capital cost?

Answer: Each 3D printer will require an operator to start the machine before it begins an automated process of creating the uploaded design. Therefore, when using 3D printing for manufacturing, the labor costs are significantly lower as there is no need for skilled machinists or operators to form part of the process.

Reflective: reduction of manpower when producing 3d printed components translates to lower capital cost

Q5: Does mass production of 3d printed components lower the capital cost?

Answer: In majority of mass production needs, 3D printing delivers a lower amount of waste than traditional manufacturing.

Reflective: less usage of material, less waste, calls for a lower cost when prodcuing a mass of 3d printed components

Q6: Does customization of 3d printed components inhabit the lowering of capital cost?

Answer: Yes, lower number of production steps design, prototype and manufacture highly complex and/or customized products.

Reflective: ease of production of 3d components inhabits lower capital cost

Theme: 3 - Maintainability

Q1: Speed is an important aspect in the construction industry. Do you think the 3d printed components make the operability of maintainability, of which makes the maintenance process easier and increase the speed during the replacement of the façade of an office building?

Answer: Yes, the whole production line can be adjusted and adapted with the speed of the printing production line. Therefore, improvements of the machinery, adjustments to the print speed or even a change of product can be made almost instantly.

Reflective: replacement of 3d components take shorter time since it requires less resources and manpower

Q2: How do you think maintainability of 3D printed materials/components impact the operational cost of the façade of an office building in terms of ease of maintenance or replacement?

Answer: If maintained properly, assets in a manufacturing plant can operate for many years. But inevitably, a machine will become outdated and spare parts may be difficult to find or too expensive to order. Keep an older asset running longer by outsourcing the 3D printing of discontinued, high-value parts.

Reflective: durability of the components requires less maintenance, less resources and manpower, which reduces the operational cost

Theme: 4 - Replacement

Q1: Does the replacement of 3D printed components/materials used in constructing the façade of an office building take longer or shorter time as compared to the replacement of components or materials used in traditional modes of construction?

Probe: Is the replacement time shorter or longer for 3D printing materials or components?

Answer: replacement of 3D printed components takes shorter time in comparison to the replacement of components used in traditional modes because 3d printer requires less process, labor, equipment's, and material

Reflective: ease of production of 3d printed components with less usage of materials makes the duration shorter for replacement process in comparison to the traditional way of construction

Q2: Does the 3d printed components require any specialized skillful personnel for replacement?

Answer: No, there is no need for skilled machinists or operator to form part of the process.

Reflective: the ease of usability and applicability of 3d printed components dispenses the need for skilled personnel during the replacement

Theme: 5 - Maintenance

Q1: What is the estimated ongoing maintenance cost for 3D printing components used in constructing the façade of an office building? Does the maintenance cost translate to low or high operational cost?

Answer: the maintenance cost can reach thousands of dollars yearly depending on the nature of the project. Maintenance cost doesn't translate to high operational cost.

Reflective: the components are not that expensive since the materials are the building materials being used which doesn't increase the operational cost

Q2: How frequent is it required for the maintenance of the façade of an office building constructed using 3D printing technology?

Probe: If frequent checking is required, do you think this raises the cost of maintenance and ultimately the operational cost?

Answer: frequent checking is not required. on a yearly basis maintenance if needed

Reflective: durability of the 3d components requires less maintenance and operational costs

Theme: 1 - Durability

Title: Senior architect engineer

Experience: 4.5

Position: senior engineer

Date: 23/3/2019

Location: governmental entity

Interviewer: Maryam AlZarooni

Interviewee: interviewee 3

Q1: What is your opinion on the durability of 3D printing components in a façade of an office building?

Probe: does 3d printed components quality influence capital cost? Does it make it higher?

Answer: 3d printed components are durable, strong, and useful. And this influences the capital cost by reducing the material usage

Reflective: the reduction of material usage will definitely reduce the capital cost

Q2: Does 3d printed components require less use of resources in production?

Answer: yes, it does, especially when it comes to labor and usage of equipment

Reflective: with less use of resources, it reduces the manpower and equipment, which reduces the capital cost

Q3: Does the usage of less material influence the waste management and cost?

Answer: yes of course it does, less usage of material means less waste, and that will save money to buy new material when needed

Reflective: the less usage of material,will reduce the waste and the capital cost when it comes to purchasing new material

Q4: Does increasing the service life of 3d components have an influence on the capital cost?

Answer: I believe it will affect on the long term, when it comes to maintain and replacing the parts the cost will be lower

Reflective: since the replacement parts are going to be lower on the long term, this will influene the reduction of the overall capital cost

Q5: Does producing very durable strong 3d component lead to high capital cost?

Answer: I think it depends if there is a wide range competition, but also, I think it may higher the capital cost

Reflective: studies state that durable 3d components lead to low capital cost

Theme: 2 – Usability and Applicability

Q1: Does ease of installation of 3D printing elements reduce the labor or workforce required thus translating to a reduced capital cost required in constructing the façade of an office building?

Answer: yes, it will, if we exchanged 100 labors by a 3D printer then it will of course reduce the capital cost

Reflective: reduction of manpower will reduce the capital cost

Q2: Does the short supply chain involved in 3D printing of components contribute to lower capital cost of using 3d printing?

Answer: yes, it does, printing the supply will be cheaper

Reflective: the short supply chain invloved in 3d printing of components will contribute to lower operational cost, thus this will influence the reduction of the capital cost

Q3: Do you think that products or materials are printed on-site thus translating to a significant reduction in the cost of transportation?

Answer: yes, because it will save cost and money of the transportation

Reflective: printing on site will reduce material waste as well as the transportation cost , thus will reduce the capital cost

Q4: An important perspective of the capital cost in the construction industry is production. Does applicability of 3Dprinting components used in constructing the façade of an office building reduce the cost of production and ultimately the capital cost?

Probe: Does reduced production cost translate to a reduction in the capital cost?

Answer: yes, since the required parts are going to be printed this will reduce the cost

Reflective: printing required components will lower the usage of material and resources , thus reducing the capital cost

Q5: Does mass production of 3d printed components lower the capital cost?

Answer: maybe not, because the demand may not match the mass production

Reflective: 3d prinitng produce customized masses with less wastage , of which reduce the capital cost

Q6: Does customization of 3d printed components inhabit the lowering of capital cost?

Answer: maybe it will because customization means producing something new so it will cost more

Reflective: 3d printers allow to produce customized printed components with lower cost, since it uses less material, less waste, and production process

Theme: 3 - Maintainability

Q1: Speed is an important aspect in the construction industry. Do you think the 3d printed components make the operability of maintainability, of which makes the maintenance process easier and increase the speed during the replacement of the façade of an office building?

Answer: yes, it is much faster than the traditional way

Reflective: 3d printer uses less material and a faster way for producing a component for replacement rather than traditional methods

Q2: How do you think maintainability of 3D printed materials/components impact the operational cost of the façade of an office building in terms of ease of maintenance or replacement?

Answer: I believe it will lower the cost

Reflective: maintainability of 3D printed materials/components will reduce the operational cost, when it comes to replacing a component since its easily reprinted

Theme: 4 - Replacement

Q1: Does the replacement of 3D printed components/materials used in constructing the façade of an office building take longer or shorter time as compared to the replacement of components or materials used in traditional modes of construction?

Probe: Is the replacement time shorter or longer for 3D printing materials or components?

Answer: it will take shorter time as compared to the replacement of components or materials used in traditional modes

Reflective: it will take shorter since the replacement of a component on 3d printer doesn't require manpower, heavy equipment, and plenty of resources

Q2: Does the 3d printed components require any specialized skillful personnel for replacement?

Answer: no don't think so it requires since the printer prints the components accordingly

Reflective: the printer prints the component and it can be assembled easily

Theme: 5 - Maintenance

Q1: What is the estimated ongoing maintenance cost for 3D printing components used in constructing the façade of an office building? Does the maintenance cost translate to low or high operational cost?

Answer: it depends on the nature and size of the project; it translates to low operational cost

Reflective: the components have high durability and their service life can be increased which may lead to lower operational cost

Q2: How frequent is it required for the maintenance of the façade of an office building constructed using 3D printing technology?

Probe: If frequent checking is required, do you think this raises the cost of maintenance and ultimately the operational cost?

Answer: it requires frequent checking and yes it will increase the cost depending on how many numbers of maintenance is required

Reflective: the components are durable, so it doesn't require frequent checking, therefore it reduces the operational cost

Theme: 1 - Durability

Title: principle architectural design engineer

Experience: 20 years

Position: Principal Architect

Date: 24-3-2019

Location: governmental entity

Interviewer: Maryam AlZarooni

Interviewee: interviewee 4

Q1: What is your opinion on the durability of 3D printing components in a façade of an office building?

Probe: does 3d printed components quality influence capital cost? Does it make it higher?

Answer: 3D printed components Considered as Durable Solution for Building Facades with lower capital cost

Reflective: durable 3d printed components reduce capital cost

Q2: Does 3d printed components require less use of resources in production?

Answer: 3d printed components require less Resource But high Qualification

Reflective: less manpower and material are used in the production of 3d printed components

Q3: Does the usage of less material influence the waste management and cost?

Answer: It Can Reduce the waste Cost of pre-Form Components and Pre-Construction Procedures Workflow Material As it will Be direct Printed to the required Shapes

Reflective: the reduction in the usage of the resources in the production of the components reduces the waste and cost

Q4: Does increasing the service life of 3d components have an influence on the capital cost?

Answer: it will reduce the capital cost as increasing the quality of the product will make it work for long life time

Reflective: highly quality printed 3d components result in low maintenace and operational cost thus reduces the capital cost

Q5: Does producing very durable strong 3d component lead to high capital cost?

Answer: if we use a high strong durable 3d component will increase the capital cost unless we can produce this component in Optimized industry & manufacturing way to reduce the production cost for the raw material

Reflective: producing very durable components may result in an increase of the initial cost but on the long term their durability and high quality will influence the reduction of the opertional cost of which will influence the capital cost as well.

Theme: 2 – Usability and Applicability

Q1: Does ease of installation of 3D printing elements reduce the labor or workforce required thus translating to a reduced capital cost required in constructing the façade of an office building?

Answer: maybe it will reduce the difficulty of current construction workflow but it will not reduce the capital cost till this new 3d print techniques to be common in the construction field. And not requiring high qualified team and designers

Reflective: since 3d printing is becoming common in the construction industry and it ease of usability and applicabilty may translate to reduce cost since less manpower and equipments are being used

Q2: Does the short supply chain involved in 3D printing of components contribute to lower capital cost of using 3d printing?

Answer: As soon as 3dprinting in construction being common method it will lower the capital cost related to the short supply chain

Reflective: short supply chain of 3d printed components contribute to lower cost since the transportation, labor , and installation costs are reduced

Q3: Do you think that products or materials are printed on-site thus translating to a significant reduction in the cost of transportation?

Answer: No, as you have to consider the transportation of the 3d print Core Material As the base for the 3d print method instead of the current material transportation

Reflective: printing on site translates to a reduction is the transportation cost since the components are being printed directly on site and only the transportation of the 3d printer cost is required

Q4: An important perspective of the capital cost in the construction industry is production. Does applicability of 3Dprinting components used in constructing the façade of an office building reduce the cost of production and ultimately the capital cost?

Probe: Does reduced production cost translate to a reduction in the capital cost?

Answer: I don't think it will reduce the production cost to that limit

Reflective: the ease of applicabilty and less usage of resources during the production may result in a cost reduction

Q5: Does mass production of 3d printed components lower the capital cost?

Answer: may be Mass production is the solution to reduce the cost of 3d printing in the construction field

Reflective: ease of a mass production lowers the capital cost

Q6: Does customization of 3d printed components inhabit the lowering of capital cost?

Answer: customization of the 3d printed component is essential as if we will neglect this part , better to return to the prefabricated modules component at factories side , And it is the basic core of the freedom of the 3d print , it will not inhabit the lowering of the capital cost as the time for any 3d printed part not depend on its complexity of shape but on its volume and Material Mass to be produced

Reflective: since 3d printed components are produced easily and can inhabit several forms from simple to sophisticated designs therefore the cost depends on mass customization. The cost can be lowered by mass production at the same time offering customized components

Theme: 3 - Maintainability

Q1: Speed is an important aspect in the construction industry. Do you think the 3d printed components make the operability of maintainability, of which makes the maintenance process easier and increase the speed during the replacement of the façade of an office building?

Answer: sure, replacing 3d printed part will be so easier and it will be no need for keeping the extra material resources within the construction itself as it will be ordered later in case of need only

Reflective: the ease of production and usage of less resources accelerates the replacement process

Q2: How do you think maintainability of 3D printed materials/components impact the operational cost of the façade of an office building in terms of ease of maintenance or replacement?

Answer: just order the required replace part or just click on print for the model in case of the availability of the printer in the near locations

Reflective: on site printing eases the replacement process, as well as printing durable material with high quality reduces the operational cost

Theme: 4 - Replacement

Q1: Does the replacement of 3D printed components/materials used in constructing the façade of an office building take longer or shorter time as compared to the replacement of components or materials used in traditional modes of construction?

Probe: Is the replacement time shorter or longer for 3D printing materials or components?

Answer: I think it will be shorter and replacement will be done 100% as required and as per the original parts

Reflective: it will be shorter in comparison to traditional way since the material is ordered from the program and printed neglecting manpower, resources, and design

Q2: Does the 3d printed components require any specialized skillful personnel for replacement?

Answer: after print the part regular skilled person will be enough for the replacement procedures

Reflective: ease of usability and applicability of 3d printed components passes up the need of a professional for replacement

Theme: 5 - Maintenance

Q1: What is the estimated ongoing maintenance cost for 3D printing components used in constructing the façade of an office building? Does the maintenance cost translate to low or high operational cost?

Answer: will be as regular as the current method of ongoing maintenance cost

Reflective: if the components are of a high quality then low maintenance cost because the service life increases, yet they are building materials that require maintenance as any other material depending on the necessity

Q2: How frequent is it required for the maintenance of the façade of an office building constructed using 3D printing technology?

Probe: If frequent checking is required, do you think this raises the cost of maintenance and ultimately the operational cost?

Answer: no extra frequent maintenance procedures required, just regular checking workflow will be ok, so no increase in cost

Reflective: the normal maintenance workflow will be adequate to maintain the quality

Theme: 1 - Durability

Title: Architect

Experience: 12

Position: Principal Architect

Date: 24/03/2019

Location: consultancy office

Interviewer: Maryam Anwar Al Zarooni

Interviewee: Interviewee 5

Q1: What is your opinion on the durability of 3D printing components in a façade of an office building?

Probe: does 3d printed components quality influence capital cost? Does it make it higher?

Answer: The 3D printing make time saving for the construction period. Yes, the 3d printed components quality influence capital cost. It makes it lower.

Reflective: durable 3d components are of a high quality of which reduces the maintenance cost, thus influences the reduction of the capital cost

Q2: Does 3d printed components require less use of resources in production?

Answer: Yes, it requires less manpower, save the transportation of materials, labors, etc.

Reflective: 3d printed components are printed easily and consume less material and resources

Q3: Does the usage of less material influence the waste management and cost?

Answer: Yes, in 3D printing has no waste of material, therefore, it will reduce the cost of waste management in the site.

Reflective: usage of less material while printing the componentsts lowers the waste and cost

Q4: Does increasing the service life of 3d components have an influence on the capital cost?

Answer: The 3D printing decreases the capital cost, since it decreases the cost of maintenance.

Reflective: high quality 3d printed components interpret to lower operational cost, thus lowers the capital cost

Q5: Does producing very durable strong 3d component lead to high capital cost?

Answer: No, it will make the building/ product stronger and it will increase the lifetime.

Reflective: producing very durable strong 3d components lead to low maintenance cost

Theme: 2 – Usability and Applicability

Q1: Does ease of installation of 3D printing elements reduce the labor or workforce required thus translating to a reduced capital cost required in constructing the façade of an office building?

Answer: Yes, since the reducing of the labor, it will reduce the capital cost.

Reflective: ease of applicabilty of 3d printed componets reduces the workforce and the capital cost

Q2: Does the short supply chain involved in 3D printing of components contribute to lower capital cost of using 3d printing?

Answer: It will lower the cost since less entities' profits.

Reflective: short supply chain interpret to lower capital cost

Q3: Do you think that products or materials are printed on-site thus translating to a significant reduction in the cost of transportation?

Answer: Sure, it will reduce the cost of transportation because it will be printed on site

Reflective: ease of production by printing on site will contribute to a reduction in the transportation cost

Q4: An important perspective of the capital cost in the construction industry is production. Does applicability of 3Dprinting components used in constructing the façade of an office building reduce the cost of production and ultimately the capital cost?

Probe: Does reduced production cost translate to a reduction in the capital cost?

Answer: Yes, it will be low cost.

Reflective: ease of production contributes in lowering cost by using less resources

Q5: Does mass production of 3d printed components lower the capital cost?

Answer: Yes, less woorkmanship, less transportation.

Reflective: mass production of 3d printed components lowers the capital cost

Q6: Does customization of 3d printed components inhabit the lowering of capital cost?

Answer: The 3D printing can print any custom design without affecting the cost.

Reflective: customization doesn't alter the cost since it's a built to order configuration, mass production reduces the cost, therefore mas customization can produce customized components , while maintaining low price by the mass production

Theme: 3 - Maintainability

Q1: Speed is an important aspect in the construction industry. Do you think the 3d printed components make the operability of maintainability, of which makes the maintenance process easier and increase the speed during the replacement of the façade of an office building?

Answer: The 3D printing will reduce the cost and reduce the maintenance.

Reflective: the replacement of components is easier and faster since they are easily printed and replaced on site

Q2: How do you think maintainability of 3D printed materials/components impact the operational cost of the façade of an office building in terms of ease of maintenance or replacement?

Answer: It will be easier to maintain and to replace.

Reflective: ease of production and usage of the printed components contribute to ease of maintenance and replacement

Theme: 4 - Replacement

Q1: Does the replacement of 3D printed components/materials used in constructing the façade of an office building take longer or shorter time as compared to the replacement of components or materials used in traditional modes of construction?

Probe: Is the replacement time shorter or longer for 3D printing materials or components?

Answer: In 3D printing, the replacement will be faster, and less cost, since no transportation and less workmanship.

Reflective: the replacement of 3d components is easier and faster than the traditional method because of its ease of production and usage

Q2: Does the 3d printed components require any specialized skillful personnel for replacement?

Answer: It need only the 3D designer, no professional or skillful labor.

Reflective: a skilled workmanship can replace a 3d printed component easily

Theme: 5 - Maintenance

Q1: What is the estimated ongoing maintenance cost for 3D printing components used in constructing the façade of an office building? Does the maintenance cost translate to low or high operational cost?

Answer: the maintenance cost translates to low operational cost.

Reflective: durable 3d printed component with high quality translate to lower maintenance cost, yet building materials require maintenance depending on its necessity

Q2: How frequent is it required for the maintenance of the façade of an office building constructed using 3D printing technology?

Probe: If frequent checking is required, do you think this raises the cost of maintenance and ultimately the operational cost?

Answer: 3D printing doesn't require frequent maintenance, which will reduce the operational cost.

Reflective: regular maintenance workflow is required depending on the necessity

Theme: 1 - Durability

Title: Architect

Experience: 12 years

Position: Architect

Date: 24-3-2019

Location: Freelance

Interviewer: Maryam AlZarooni

Interviewee: interviewee 6

Q1: What is your opinion on the durability of 3D printing components in a façade of an office building?

Probe: does 3d printed components quality influence capital cost? Does it make it higher?

Answer: durability of 3d printed components are too similar to the traditional components. the initial cost of 3d printing will increase the cost, but from another aspects of labor, material, and reduction of human faults it will be lower in cost

Reflective: 3d printed components are of a high strength and quality translate to low material and maintenance cost of which influences the capital cost

Q2: Does 3d printed components require less use of resources in production?

Answer: yes of course reduction of factory production

Reflective: 3d printed components require less use of material and workforce in production

Q3: Does the usage of less material influence the waste management and cost?

Answer: more accuracy in calculation of required material, which will reduce cost and waste, and assumptions of any calculations

Reflective: usage of less material reduces the waste and cost

Q4: Does increasing the service life of 3d components have an influence on the capital cost?

Answer: depend on the treatment used to improve the material quality; if it's expensive it will increase the cost

Reflective: durable high strength components interpret to lower operational cost

Q5: Does producing very durable strong 3d component lead to high capital cost?

Answer: durable strong 3d component lead to high cost

Reflective: producing very durable strong 3d component may lead to higher cost but the reduction of several resources contribute to lower capital and operational costs

Theme: 2 – Usability and Applicability

Q1: Does ease of installation of 3D printing elements reduce the labor or workforce required thus translating to a reduced capital cost required in constructing the façade of an office building?

Answer: yes, it will reduce human resources, transportation, and time, which will reduce the cost

Reflective: on site prinitng of the components translates to ease of installation and less usage of resources

Q2: Does the short supply chain involved in 3D printing of components contribute to lower capital cost of using 3d printing?

Answer: since it's printed on site it reduces the supply chain itself and mitigate the risk of any damages that may happen during transportation

Reflective: ease of production and installation of 3d printed components reduces the supply chain and lowers the cost

Q3: Do you think that products or materials are printed on-site thus translating to a significant reduction in the cost of transportation?

Answer: yes, it reduces the transportation cost and any transportation accident that may lose the whole product

Reflective: materials that are printed on site reduces the transportation cost

Q4: An important perspective of the capital cost in the construction industry is production. Does applicability of 3Dprinting components used in constructing the façade of an office building reduce the cost of production and ultimately the capital cost?

Probe: Does reduced production cost translate to a reduction in the capital cost?

Answer: considering less usage of human resources, supply chain, transportation, accuracy of material will reduce the cost

Reflective: ease of production of the 3d printed components by using less resources interprets to a reduction on the capital cost

Q5: Does mass production of 3d printed components lower the capital cost?

Answer: depends on the unit of material (quantity, hours, power) being used the capital cost will be influenced by the quanitiy

Reflective: mass production of 3d printed components reduces the capital cost based on the mass and volume

Q6: Does customization of 3d printed components inhabit the lowering of capital cost?

Answer: it will lower the cost because of the technology used in printing the components

Reflective: since it's build based on an order technology, customization doesn't alter the cost, it can be lowered by the usage of less resources at production

Theme: 3 - Maintainability

Q1: Speed is an important aspect in the construction industry. Do you think the 3d printed components make the operability of maintainability, of which makes the maintenance process easier and increase the speed during the replacement of the façade of an office building?

Answer: the product will be available in a very short time of which speeds up the replacement process

Reflective: availability of the component based on its flexible production accelerates the replacement of the elements

Q2: How do you think maintainability of 3D printed materials/components impact the operational cost of the façade of an office building in terms of ease of maintenance or replacement?

Answer: after the component is printed it considered a material after all if its high-quality material it will increase the service life of the product which will eventually will reduce the operational cost and future replacements

Reflective: high quality 3d printed components translate to a lower operational cost

Theme: 4 - Replacement

Q1: Does the replacement of 3D printed components/materials used in constructing the façade of an office building take longer or shorter time as compared to the replacement of components or materials used in traditional modes of construction?

Probe: Is the replacement time shorter or longer for 3D printing materials or components?

Answer: it's going to be shorter because the production of the components will be faster by printing it

Reflective: fast production of printed 3d components speeds up the replacement of the parts in comparison to the traditional method that requires different resources

Q2: Does the 3d printed components require any specialized skillful personnel for replacement?

Answer: yes, a skilled technician is a must to replace any part to avoid any damages

Reflective: 3d printed components are usable therefore any technician can replace the element

Theme: 5 - Maintenance

Q1: What is the estimated ongoing maintenance cost for 3D printing components used in constructing the façade of an office building? Does the maintenance cost translate to low or high operational cost?

Answer: if it's a good product of a high quality it will reduce the estimated cost this translate to lower operational cost

Reflective: high durable components translate to lower maintenance cost

Q2: How frequent is it required for the maintenance of the façade of an office building constructed using 3D printing technology?

Probe: If frequent checking is required, do you think this raises the cost of maintenance and ultimately the operational cost?

Answer: frequent checking is a must, but replacing the components may not be needed due to the quality of the products

Reflective: since 3d printing produces highly durable product which are of high quality, frequent checking is not required

Theme: 1 - Durability

Title: Sr. Researcher

Experience: 4 years

Position: Head of 4IR

Date: 25/03/2019

Location: governmental entity

Interviewer: Maryam AlZarooni

Interviewee: interviewee 7

Q1: What is your opinion on the durability of 3D printing components in a façade of an office building?

Probe: does 3d printed components quality influence capital cost? Does it make it higher?

Answer: The durability of the 3D printing depends on the selected material and the method of printing. If stainless steel was used the cost will increase sky fold. If the speed of printing is controlled, more reliable material is expected. If the quality is increased, that mean by default the capital cost will increase, and it make it more expensive.

Reflective: high quality printed components can increase the capital cost, but for the long term it will decrease the maintenance cost

Q2: Does 3d printed components require less use of resources in production?

Answer: Yes, the 3d require less resource, since you are controlling the amount of material that is needed, through the printing process.

Reflective: 3d printed components require less resources

Q3: Does the usage of less material influence the waste management and cost?

Answer: Yes, since using less material, ensure less waste to handle. Less waste to handle ensures reduction in the cost.

Reflective: less usage of material will decrease the waste and lowers the cost

Q4: Does increasing the service life of 3d components have an influence on the capital cost?

Answer: Yes, if the service life of a 3D components can last longer, that mean by default the price will be increased. Since, we are getting better quality.

Reflective: high quality 3d printed components translates to lower maintenance cost

Q5: Does producing very durable strong 3d component lead to high capital cost?

Answer: Yes, it all depends on the supply and demand. But, basically better-quality lead to high capital cost.

Reflective: producing strong material that lasts longer than its service life will eventually require less maintenance and lower operational costs

Theme: 2 – Usability and Applicability

Q1: Does ease of installation of 3D printing elements reduce the labor or workforce required thus translating to a reduced capital cost required in constructing the façade of an office building?

Answer: True, ease of installation always reduces the cost. But currently, the 3D technology price is higher than regular traditional way.

Reflective: ease of installation of 3D printing elements reduce the manpower and cost

Q2: Does the short supply chain involved in 3D printing of components contribute to lower capital cost of using 3d printing?

Answer: False, there are few companies involved with 3D printing of structure. This mean, few companies can provide the supply, which lead to increase in the price.

Reflective: short supply chain involved with 3d printing lowers the cost since printing can be on-site

Q3: Do you think that products or materials are printed on-site thus translating to a significant reduction in the cost of transportation?

Answer: Yes, if material is printed on site, there is less chance the item getting damage through transportation.

Reflective: materials that are printed on-site reduces the cost of transportation

Q4: An important perspective of the capital cost in the construction industry is production. Does applicability of 3Dprinting components used in constructing the façade of an office building reduce the cost of production and ultimately the capital cost?

It all depends on the cost of printing, if the total cost and duration printing is less than traditional method, than the cost will be lower.

Probe: Does reduced production cost translate to a reduction in the capital cost?

Answer: Yes, if cost of 3D printing is less than traditional method, than the capital cost will be lower and reduced.

Reflective: less usage of resources leads to a lower production cost and capital cost

Q5: Does mass production of 3d printed components lower the capital cost?

Answer: Yes, mass production can be achived if items are being printed fast enough, which will lead to reduction in captial cost.

Reflective: mass production of 3d printed components reduces the capital cost

Q6: Does customization of 3d printed components inhabit the lowering of capital cost?

Answer: 3d print can be customize to any shape easily, it is not related to the capital cost in my opinion.

Reflective: customization of 3d printed components wont alter the cost since its printed in any form you design it might lower by the concept of using less resources interms of materials and manpower

Theme: 3 - Maintainability

Q1: Speed is an important aspect in the construction industry. Do you think the 3d printed components make the operability of maintainability, of which makes the maintenance process easier and increase the speed during the replacement of the façade of an office building?

Answer: Yes, since using 3D printing allow less maintenance item to be stocked and printing the required item if needed.

Reflective: the 3d elements can be produced easily of which speeds up the replacement

Q2: How do you think maintainability of 3D printed materials/components impact the operational cost of the façade of an office building in terms of ease of maintenance or replacement?

Answer: It help a lot with maintenance, since item are not stocked, and the maintenance can be printed on site directly.

Reflective: the operational cost is lowered due to ease of maintenance and replacement of the printed parts

Theme: 4 - Replacement

Q1: Does the replacement of 3D printed components/materials used in constructing the façade of an office building take longer or shorter time as compared to the replacement of components or materials used in traditional modes of construction?

Probe: Is the replacement time shorter or longer for 3D printing materials or components?

Answer: The replacement should be faster, since the printer will be on site and ready to print. If the printer is not in the site, it will take longer.

Reflective: ease of production and installation of 3d printed components quickens the replacement

Q2: Does the 3d printed components require any specialized skillful personnel for replacement?

Answer: A skillful person is required, since handling 3D printing in large scale required certain pre setup that should be followed.

Reflective: a skillful might be required for programming, but for assembly and replacement a technician can replace due to the 3d printed components ease of usability and applicability

Theme: 5 - Maintenance

Q1: What is the estimated ongoing maintenance cost for 3D printing components used in constructing the façade of an office building? Does the maintenance cost translate to low or high operational cost?

Answer: The printing of the maintenance items leads to a lower operational cost.

Reflective: maintenance of 3D printing components reduces the operational cost

Q2: How frequent is it required for the maintenance of the façade of an office building constructed using 3D printing technology?

Probe: If frequent checking is required, do you think this raises the cost of maintenance and ultimately the operational cost?

Answer: It all depends on the quality of the printed part, if the quality of the printed part is high. It doesn't require a lot of maintenance, which ultimately lead to a lower operational cost.

Reflective: depends on the printed component and since they are usually of high quality then it lowers the operational cost

Theme: 1- Durability

Title: Engineer

Experience: 10 Years

Position: Area Manager - Capital Projects

Date: 25/3/2019

Location: private sector

Interviewer: Maryam AlZarooni

Interviewee: interviewee 8

Q1: What is your opinion on the durability of 3D printing components in a façade of an office building?

Probe: does 3d printed components quality influence capital cost? Does it make it higher?

Answer: Taking in consideration that the components are built in a right condition, 3D printing components are highly durable, however, it may be influenced by the workmanship

Reflective: high 3d printed components quality may contribute to higher cost of material usage but lower maintenance cost

Q2: Does 3d printed components require less use of resources in production?

Answer: As it is mostly automated, resources are relatively less particularly at post setup stage.

Reflective: printed components require less resources to produce

Q3: Does the usage of less material influence the waste management and cost?

Answer: Material and waste management are correlated, the less material the less waste and obviously less cost of disposal.

Reflective: the less the material used the less the waste the lower the cost

Q4: Does increasing the service life of 3d components have an influence on the capital cost?

Answer: The more durable, the more service life the less maintenance, as a result less capital cost to maintain the said components.

Reflective: increasing the service life of 3d components, result in lower maintenance costs, thus lower capital cost

Q5: Does producing very durable strong 3d component lead to high capital cost?

Answer: It depends on the material used and number of typical components. I believe initial cost might be higher in relation to sustaining/maintaining the components in future.

Reflective: durable strong 3d printed components lead to lower maintenance cost

Theme: 2 – Usability and Applicability

Q1: Does ease of installation of 3D printing elements reduce the labor or workforce required thus translating to a reduced capital cost required in constructing the façade of an office building?

Answer: Depending on the complexity of the elements and the installation methodology, it could reduce the installation cost, however, it is not a definite straight forward answer.

Reflective: ease of installation of the printed components reduces the resources and lowers capital cost

Q2: Does the short supply chain involved in 3D printing of components contribute to lower capital cost of using 3d printing?

Answer: If the components are printed onsite or close to, then the risk in logistics as a part of supply chain is mitigated, probably transportation cost is saved.

Reflective: on-site printing of 3d components lowers the cost

Q3: Do you think that products or materials are printed on-site thus translating to a significant reduction in the cost of transportation?

Answer: Answer can be duplicated with Q2 above, if the elements are printed on site, then transportation cost can be deducted, and in some cases could be significant

Reflective: on-site printing of 3d components lowers the transportation cost

Q4: An important perspective of the capital cost in the construction industry is production. Does applicability of 3Dprinting components used in constructing the façade of an office building reduce the cost of production and ultimately the capital cost?

Probe: Does reduced production cost translate to a reduction in the capital cost?

Answer: Taking in consideration the printing infra is set, then it will obviously directly influence the capital cost. However, there are other factors such as location of production, material used and availability of raw material etc. but in general it has commercial benefits.

Reflective: production of 3d component can be printed directly on site of which reduces the transportation as well as the less usage of resources and materials interpret to deduction of the cost

Q5: Does mass production of 3d printed components lower the capital cost?

Answer: It is not necessarily faster, but compared to conventional production lines and risk involved in machines' downtime and logistics, 3D printing could require less capital investment.

Reflective: the manufacture of the printed components is going to be faster which reduces the capital cost

Q6: Does customization of 3d printed components inhabit the lowering of capital cost?

Answer: 3D printing is customization friendly methodology compared to conventional production methodologies. Hence, it is cheaper.

Reflective: customization doesn't alter the capital cost due to its flexibility in printing of any form

Theme: 3 - Maintainability

Q1: Speed is an important aspect in the construction industry. Do you think the 3d printed components make the operability of maintainability, of which makes the maintenance process easier and increase the speed during the replacement of the façade of an office building?

Answer: Usually speed of maintenance is related to availability of spare parts, fixation details, the simpler fixation detail is the faster installation is resulted.

Reflective: 3d printing can make the maintenance process much more efficient and faster

Q2: How do you think maintainability of 3D printed materials/components impact the operational cost of the façade of an office building in terms of ease of maintenance or replacement?

Answer: If the material used is durable and reliable then it will have a longer life span in which maintenance/replacement requirement will be less.

Reflective: depends on the efficiency of the material being utilized, the higher the durability and quality the lesser the maintenance and replacement works

Theme: 4 - Replacement

Q1: Does the replacement of 3D printed components/materials used in constructing the façade of an office building take longer or shorter time as compared to the replacement of components or materials used in traditional modes of construction?

Probe: Is the replacement time shorter or longer for 3D printing materials or components?

Answer: As mentioned previously, the replacement is directly related to the complexity of the fixation details and accessibility, so speed of installation/replacement may vary.

Reflective: the replacement of a 3d component can be much faster than the traditional mode

Q2: Does the 3d printed components require any specialized skillful personnel for replacement?

Answer: It does require specialized skilled personnel to produce, furthermore, skilled personnel are needed for any type of jobs.

Reflective: a skilled personnel is required to adjust and produce a certain printing job of a component, but any technician can replace the element easily

Theme: 5 - Maintenance

Q1: What is the estimated ongoing maintenance cost for 3D printing components used in constructing the façade of an office building? Does the maintenance cost translate to low or high operational cost?

Answer: If technology is available then should be less, however, might be the opposite in case of non-availability.

Reflective: maintenance of 3d component contributes to low operational cost due to its fast production and lower resources usage

Q2: How frequent is it required for the maintenance of the façade of an office building constructed using 3D printing technology?

Probe: If frequent checking is required, do you think this raises the cost of maintenance and ultimately the operational cost?

Answer: Depends on the material and workmanship, however, it is newly introduced then I would expect more often regular checkups, this may not be a significant increase of OPEX.

Reflective: this usually depends on the quality of the printed components; if they are durable then the normal maintenance process is required.

Theme: 1 - Durability

Title: Project Architect

Experience: 15 years

Position: project manager

Date: March 25th, 2019

Location: private sector

Interviewer: Maryam Al Zarooni

Interviewee: Interviewee 9

Q1: What is your opinion on the durability of 3D printing components in a façade of an office building?

Probe: does 3d printed components quality influence capital cost? Does it make it higher?

Answer: I understand that those 3d printed components are more durable due to the "automation system" being utilized in such procedure, which in result, produces accurate measurements with less probabilities of deviations and tolerances; saying that the durability should be better. However, it remains this technology hasn't been broadly used outside laboratories and it's still believed unsuitable for every construction site.

Therefore, such preparatory requirements have their consequences on "Cost".

Reflective: the 3d components are designed and produced to be more durable than normal building components which may influence the cost, but its long service life and high-quality results in reducing the maintenance cost

Q2: Does 3d printed components require less use of resources in production?

Answer: Yes; it's a procedure has its significant reliability on "automation" and robotic controls than humans. Produced components are precise and proper with less material consumed.

Reflective: 3d components are produced with less material used

Q3: Does the usage of less material influence the waste management and cost?

Answer: Yes; to certain extent, reduced wastes have influence, as long as the material is the major factor of the cost; and whereas bringing such technology into a Site is negligible.

Reflective: production od 3d componens with less resources result in reduction of waste and cost

Q4: Does increasing the service life of 3d components have an influence on the capital cost?

Answer: No; in the perspective of a Life Cost Analysis, the Life Cycle Cost of a Component considers the Up-front cost besides the Operational Expenses due to the extended life expectancy of it and its less operational cost due to the reduced maintenance/durability. In my view, Service Life has nothing to do with the up-front, however it influences the Life Cycle Cost.

Reflective: 3d components when sustained result in lower operational costs

Q5: Does producing very durable strong 3d component lead to high capital cost?

Answer: Either Yes or No is correct; depending on the cost of the procedures been used to produce/execute/manufacture this component, whether it is negligible or not. That is to say, if the procedure is high expensive then the Capital Cost increases; whereas if the procedure is less than the savings from less wastes, then the Capital Cost should be lower.

Reflective: high quality components may add expenses on the cost, yet reduce the operational cost, therefore this influences the overall capital cost.

Theme: 2 – Usability and Applicability

Q1: Does ease of installation of 3D printing elements reduce the labor or workforce required thus translating to a reduced capital cost required in constructing the façade of an office building?

Answer: Either Yes or No is correct; i.e. reducing the workforce is a factor, however it has to be balanced with the cost of providing high skilled labor with capabilities of performing the activity of installation and production. Giving example, the cost variance by hiring Hyperbaric Welders than Regular Welders is significant.

Reflective: ease of installation of the components reduce the manpower, material usage, transportation, and design. Therefore the capital cost is reduced

Q2: Does the short supply chain involved in 3D printing of components contribute to lower capital cost of using 3d printing?

Answer: Yes, less involvers in the production process should significantly lower the capital cost. Unless other factors interfere the process, like particular specifications than conventional to be considered for the purpose of 3D printing. To my knowledge, the 3D concrete printing requires higher characteristics of concrete workability should be reached by considering additives to the concrete mix.

Reflective: shortage of the supply chain easens the production of the printed components of which contribute to lower capital cost

Q3: Do you think that products or materials are printed on-site thus translating to a significant reduction in the cost of transportation?

Answer: Yes, provided that no special materials than those “conventionally” required in the process and they should be sourced from unavailable locally material suppliers.

Reflective: lower cost of transportation for on-site prinitng

Q4: An important perspective of the capital cost in the construction industry is production. Does applicability of 3Dprinting components used in constructing the façade of an office building reduce the cost of production and ultimately the capital cost?

Probe: Does reduced production cost translate to a reduction in the capital cost?

Answer: Yes, making this technology a market available outside the premises of research labs, applicable and competitive should significantly conclude lower capital cost by applying it.

Reflective: this technology is designed to produce applicable components at your order without any complications resulting in a lowering capital cost

Q5: Does mass production of 3d printed components lower the capital cost?

Answer: Yes, standardization/unification of produced components lower the initial cost of back of house engineering, production and assembly.

Reflective: mass production offers lower cost of the production of the components, thus lowering the capital cost

Q6: Does customization of 3d printed components inhabit the lowering of capital cost?

Answer: Yes, customization results into increased engineering efforts to conclude each particular component, slow down the production and complicates site operations in assembly.

Reflective: customization of the components doesn't alter the cost since the elements are being ordered for production , but can be lowered by offering mass customization.

Theme: 3 - Maintainability

Q1: Speed is an important aspect in the construction industry. Do you think the 3d printed components make the operability of maintainability, of which makes the maintenance process easier and increase the speed during the replacement of the façade of an office building?

Answer: Provided that the 3D Printed Components have different considerations than those if they have been conventionally produced, then different methodologies have to be generated in order to accommodate/maintain/de-assemble/deal with the components.

Other probabilities reveal if special skills of Maintenance Team in dealing with Produced Elements should be assumed. However, assuming Produced Components are identical to those conventionally produced then it has nothing to deal with the maintainability compared to those conventionally produced, in short, they are the identical in maintenance procedures.

Reflective: depends on the efficiency and quality of the material being consumed when printing the components, some materials are durable enough to eliminate often maintenance, as well as its ease of production speeds up the replacement

Q2: How do you think maintainability of 3D printed materials/components impact the operational cost of the façade of an office building in terms of ease of maintenance or replacement?

Answer: Provided that different considerations of the components than those if conventionally produced, then operational cost has to be reviewed accordingly.

Reflective: ease on maintenance and replacement interprets to ease of production and applicability of the components. However high-quality materials lower the maintenance workflow

Theme: 4 - Replacement

Q1: Does the replacement of 3D printed components/materials used in constructing the façade of an office building take longer or shorter time as compared to the replacement of components or materials used in traditional modes of construction?

Probe: Is the replacement time shorter or longer for 3D printing materials or components?

Answer: Provided that the 3D Printed Components have different considerations than those if they have been conventionally produced, then different methodologies have to be generated in order to accommodate/maintain/de-assemble/deal with the components.

A judgement, whether longer or shorter, difficult or easier, depending on the Component.

Reflective: replacement of 3d printed components takes shorter than conventional method, since the production is faster and the elements are more applicable

Q2: Does the 3d printed components require any specialized skillful personnel for replacement?

Answer: Provided that the 3D Printed Components have different considerations than those if they have been conventionally produced, then different methodologies have to be generated in order to accommodate/maintain/de-assemble/deal with the components.

A judgement, whether longer or shorter, difficult or easier, depending on the Component.

Reflective: the usability of the components eases the replacement, while a skillful personnel is essential at the programming and printing of the component

Theme: 5 - Maintenance

Q1: What is the estimated ongoing maintenance cost for 3D printing components used in constructing the façade of an office building? Does the maintenance cost translate to low or high operational cost?

Answer: Yes, maintainable components, easy to de-assemble and reassemble significantly results into lower operational cost.

Reflective: ease of production and installation translate to low operational cost

Q2: How frequent is it required for the maintenance of the façade of an office building constructed using 3D printing technology?

Probe: If frequent checking is required, do you think this raises the cost of maintenance and ultimately the operational cost?

Answer: Provided that a 3D Produced Component is more durable than if it is conventionally produced then high durability is inversely proportional with the frequency of maintenance and that will translate into lower cost of maintenance.

Reflective: high durability of the printed components neglect frequent checking, hence reduces the maintenance cost

Theme: 1 - Durability

Title: Associate Project Manager

Experience: 5 years

Position: Project Manager

Date: 25/3/2019

Location: site office

Interviewer: Maryam AlZarooni

Interviewee: interviewee 10

Q1: What is your opinion on the durability of 3D printing components in a façade of an office building?

Probe: does 3d printed components quality influence capital cost? Does it make it higher?

Answer: I believe that 3D printed components are highly durable due to the constructability methodology and settings/ setup of the 3D printers. For now, yes, however, in the future when 3D printers will be vastly available it should not be.

Reflective: durable 3d printed components can have a high service life interpreting to their production, however this influences the reduction maintenance costs

Q2: Does 3d printed components require less use of resources in production?

Answer: Depending on the use. Generally, a professional would use it in the most effective way.

Reflective: printed components consume less material at production

Q3: Does the usage of less material influence the waste management and cost?

Answer: Depending on the way the material is being utilized

Reflective: the less usage of material neglects the waste of it and reduces the cost

Q4: Does increasing the service life of 3d components have an influence on the capital cost?

Answer: No, not on the capital cost since the material being used is the same whether 3D printed or not. However, the difference is in the life expectancy of the material.

Reflective: increasing life expectancy of a printed components deducts the operational cost

Q5: Does producing very durable strong 3d component lead to high capital cost?

Answer: No, it shouldn't, as the material will be the same whether 3D printed or not. The difference is in the constructability and pre-setup

Reflective: since the production of 3d components interprets high quality this may influence the capital cost but on the long run reduces the operational cost

Theme: 2 – Usability and Applicability

Q1: Does ease of installation of 3D printing elements reduce the labor or workforce required thus translating to a reduced capital cost required in constructing the façade of an office building?

Answer: Not really, since it needs qualified labors that are not easy to find. However, later on the case might be different.

Reflective: on-site printing reduces manpower and equipment utilization and the ease of applicability of the printed components reduces the cost

Q2: Does the short supply chain involved in 3D printing of components contribute to lower capital cost of using 3d printing?

Answer: Theoretically, it could. However, I don't see it happening in practical work examples/ case studies available

Reflective: shortage in supply chain reduces cost since less interference in the production. Example is an on-site printing that reduces transporation and installation costs

Q3: Do you think that products or materials are printed on-site thus translating to a significant reduction in the cost of transportation?

Answer: it might, depending on the availability of the materials

Reflective: on site printing reduces significant cost of transportation

Q4: An important perspective of the capital cost in the construction industry is production. Does applicability of 3Dprinting components used in constructing the façade of an office building reduce the cost of production and ultimately the capital cost?

Probe: Does reduced production cost translate to a reduction in the capital cost?

Answer: Yes , by using less resources and labors definitely the capital cost will reduce

Reflective: ease of production by using less resources translates to lower capital cost

Q5: Does mass production of 3d printed components lower the capital cost?

Answer: yes in a way it does by printing unified components

Reflective: mass production offers lower capital cost by building unified components and a defined volume

Q6: Does customization of 3d printed components inhabit the lowering of capital cost?

Answer: I don't think it will influence the cost, but as I said earlier skilled labors are hard to find so the assembly might raise the cost

Reflective: production of components doesn't alter the cost, and ease of installation may contribute to lower costs

Theme: 3 - Maintainability

Q1: Speed is an important aspect in the construction industry. Do you think the 3d printed components make the operability of maintainability, of which makes the maintenance process easier and increase the speed during the replacement of the façade of an office building?

Answer: it depends whether the 3d component was pre-programmed in the setting or the need to program it all over again

Reflective: the production of the components is as per order, hence speeds up the replacement and maintenance

Q2: How do you think maintainability of 3D printed materials/components impact the operational cost of the façade of an office building in terms of ease of maintenance or replacement?

Answer: preprogramming of the components should make efficient

Reflective: the manufacturing of the components is through an order configuration that eases the production, thus this inhabits fast maintenance and replacement

Theme: 4 - Replacement

Q1: Does the replacement of 3D printed components/materials used in constructing the façade of an office building take longer or shorter time as compared to the replacement of components or materials used in traditional modes of construction?

Probe: Is the replacement time shorter or longer for 3D printing materials or components?

Answer: shorter time if it is pre-programmed. Longer if we need to do the setup and programming

Reflective: due to ease of 3d components production, the replacement is shorter than conventional mode

Q2: Does the 3d printed components require any specialized skillful personnel for replacement?

Answer: Yes. Someone able to understand the engineering behind it as well. However, if the information is pre-programmed so not really.

Reflective: for the programming and setup it might require skillful personnel, whereas for replacement a skilled technician can do the replacement

Theme: 5 - Maintenance

Q1: What is the estimated ongoing maintenance cost for 3D printing components used in constructing the façade of an office building? Does the maintenance cost translate to low or high operational cost?

Answer: it depends on the quality of the material being utilized; I think it will reduce the cost

Reflective: durable materials reduce operational costs

Q2: How frequent is it required for the maintenance of the façade of an office building constructed using 3D printing technology?

Probe: If frequent checking is required, do you think this raises the cost of maintenance and ultimately the operational cost?

Answer: Not as frequent as normal methods given the engineering and efficient use of materials and components

Reflective: the usual maintenance process is required since the printed components are mostly durable and of a high quality